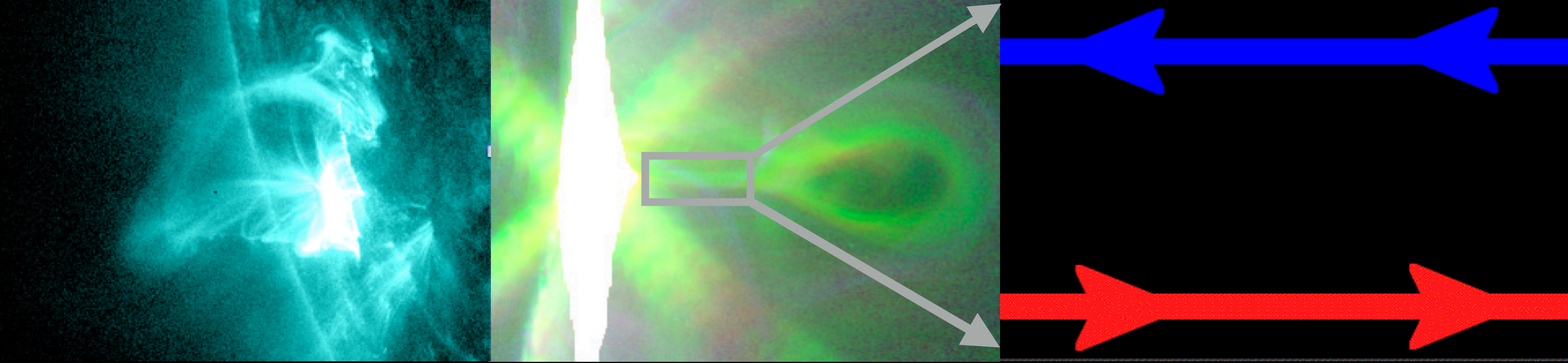

Large-scale solar eruptions and induced small-scale magnetic reconnection

Xin Cheng[1,2]

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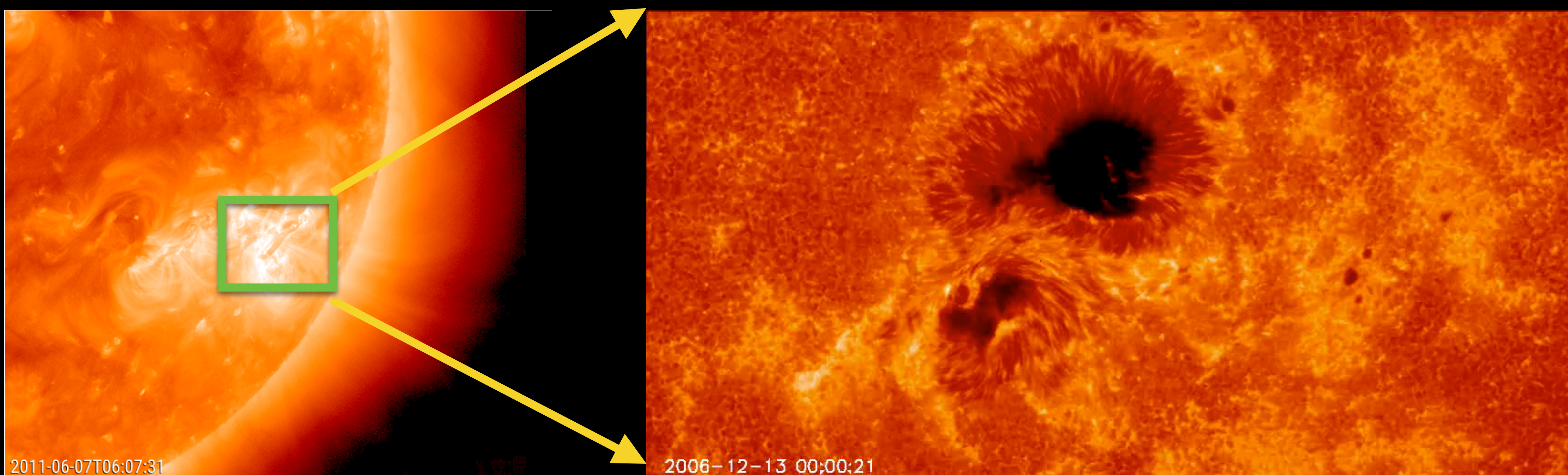
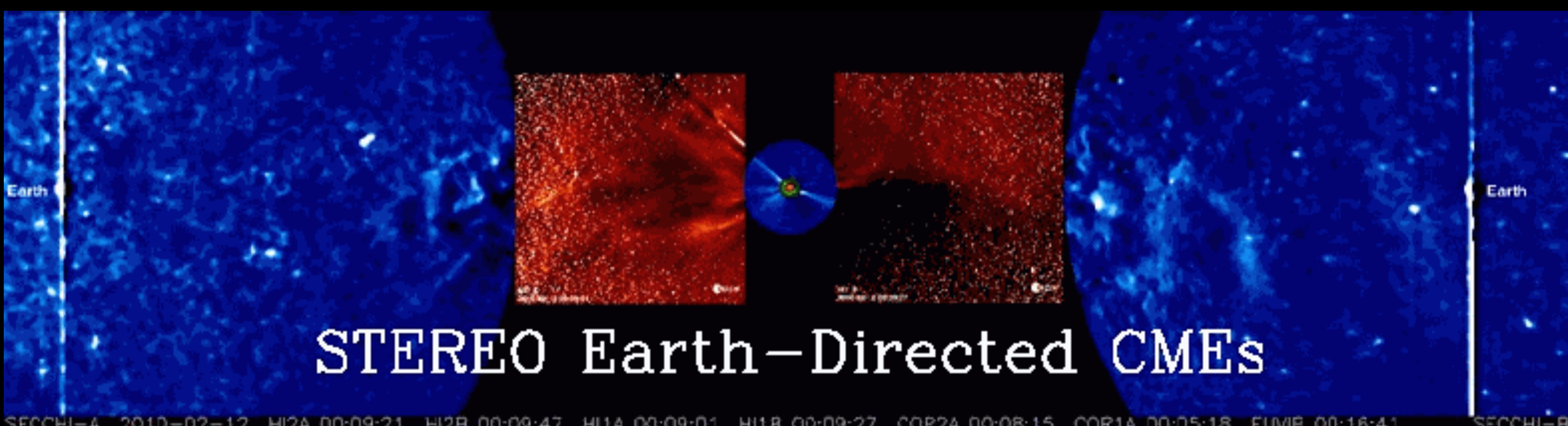
Outline

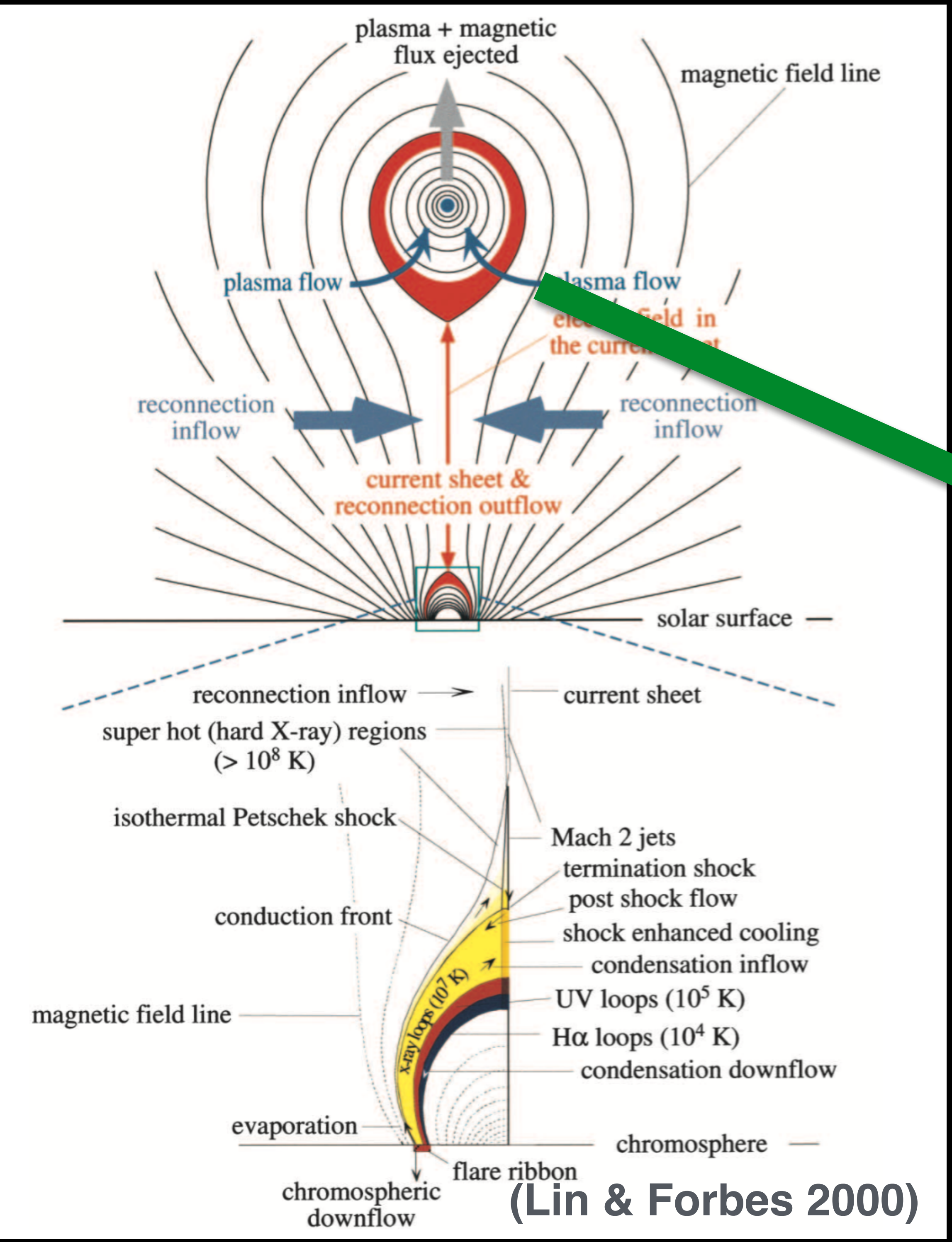
1. Background
2. Evidence of high temperature helical plasma (magnetic flux rope) existing in the corona
3. Role of magnetic flux rope in accelerating the eruption and causing the flare emission
4. Observations of induced magnetic reconnection

Two most explosive phenomena in our solar system: CMEs and Flares



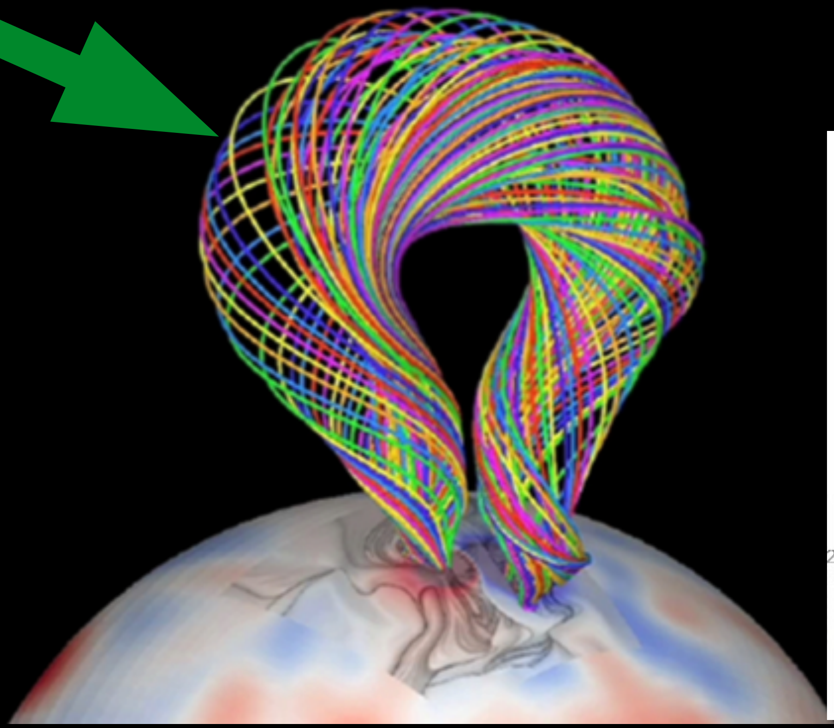


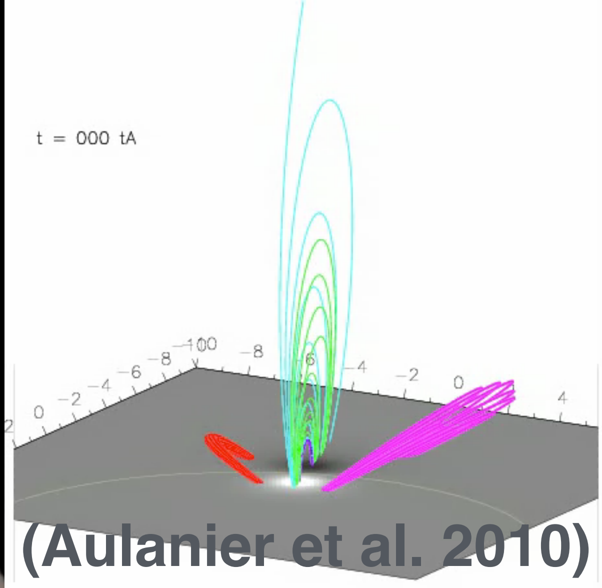
CME/flare models



(Lin & Forbes 2000)

Magnetic flux rope is believed to be the fundamental structure in the solar atmosphere. It erupts upward to become a CME and gives rise to a flare underneath at the same time (Shafranov 1966; Chen 1989; Forbes & Isenberg 1991; Shibata 1995; Titov



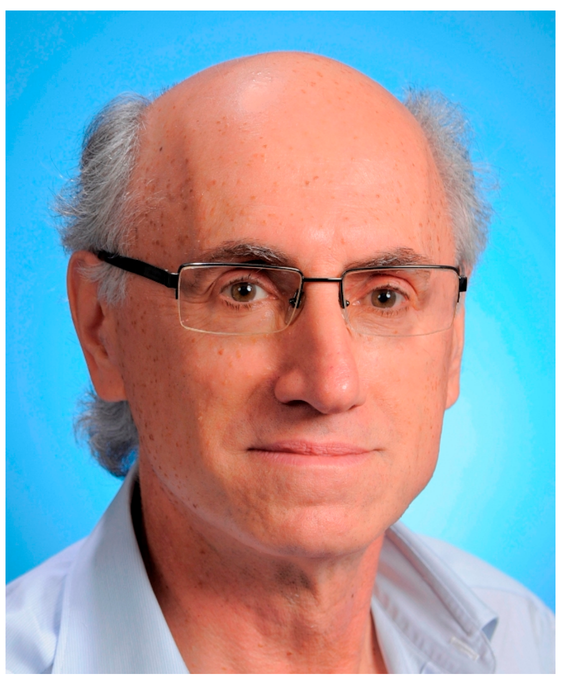


(Aulanier et al. 2010)

Controversy of pre-eruptive configuration of CMEs

Sheared arcades

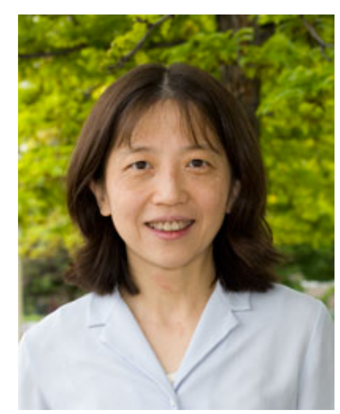
Magnetic flux ropes



S. K. Antiochos

B. Kliem

V. Vourlidas



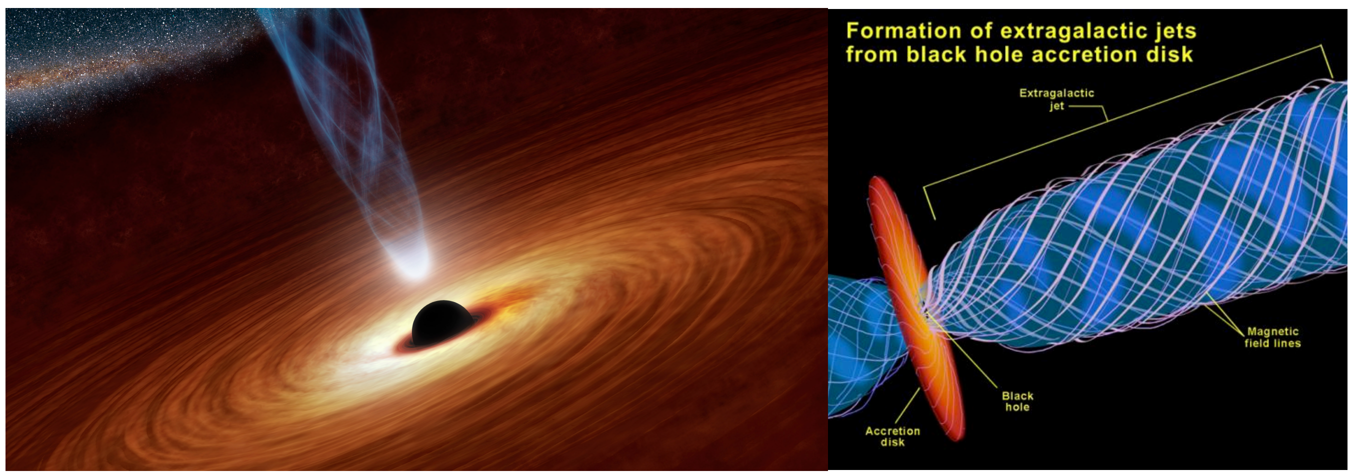
Y. Fan

G. Aulanier

What is magnetic flux rope?

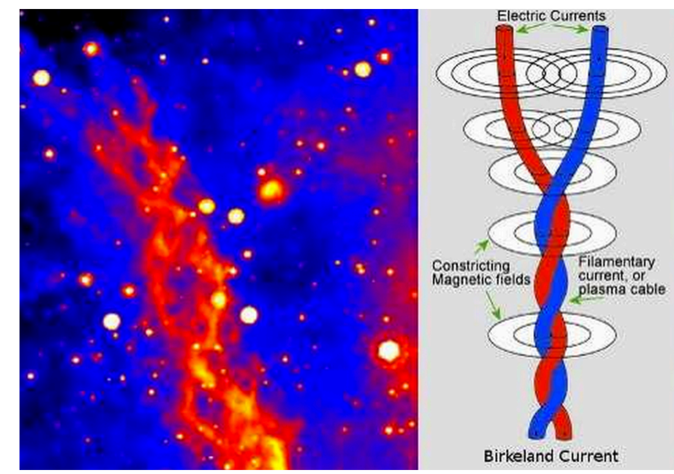
---A magnetic structure, with all magnetic field lines winding around an central axis.

Ubiquitous Magnetic Flux Rope!!



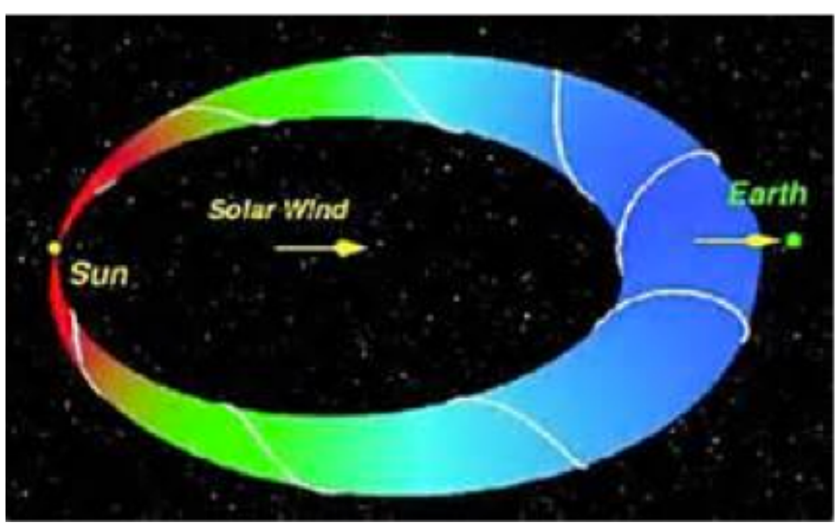
Black hole

(Meier et al. 2001)



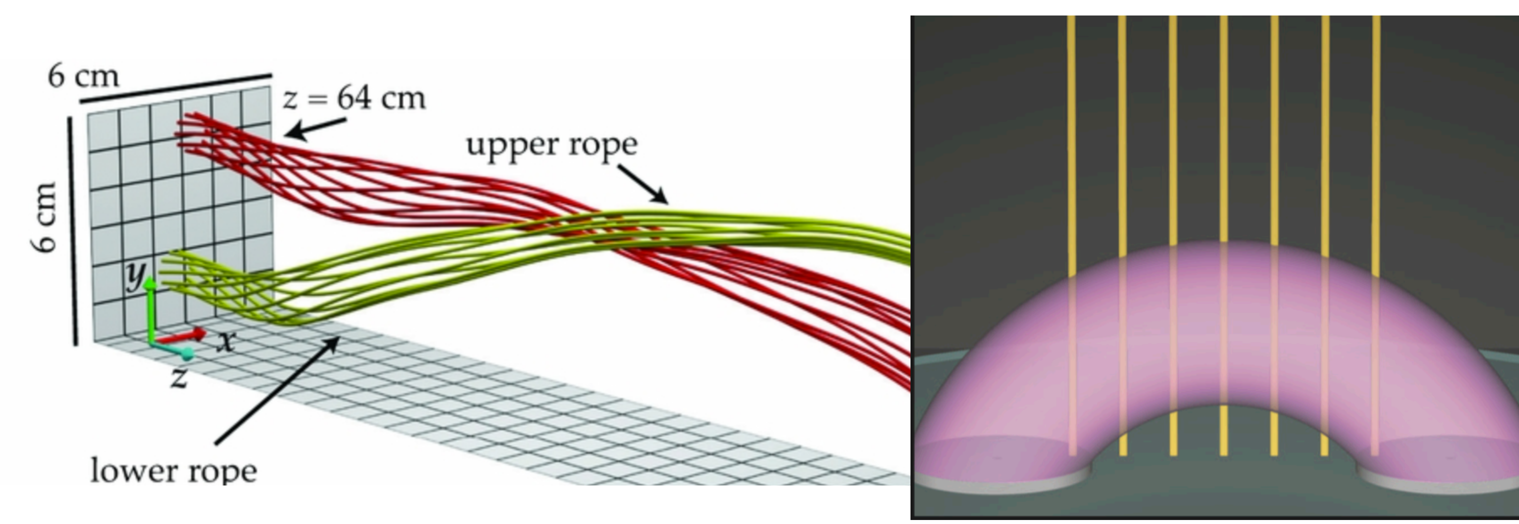
Nebula

(Morris et al. 2006)



Magnetopause

(Burlaga 1988)

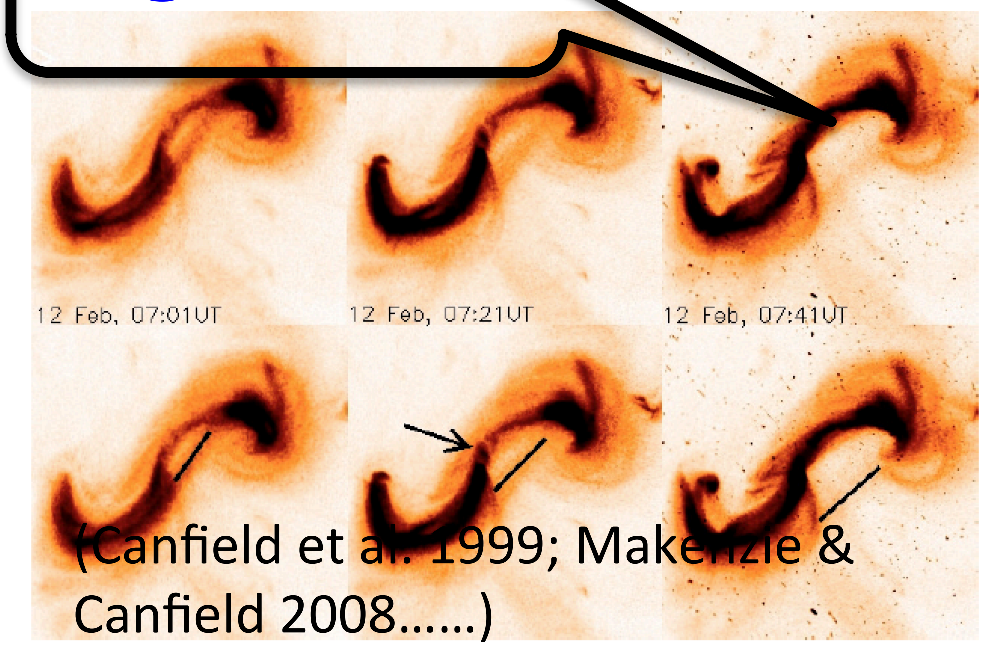


Laboratory experiment

(Gekelman et al. 2012; Myers et al. 2015)

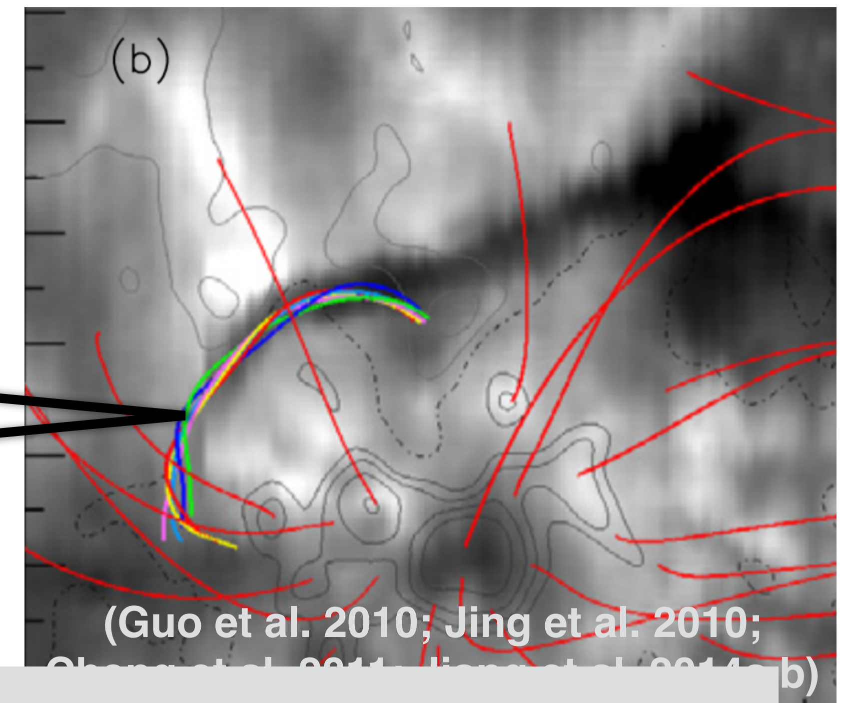
Do MFRs exist in corona, even before the eruption?

Sigmoids:



(Canfield et al. 1999; Makenzie & Canfield 2008......)

Filament

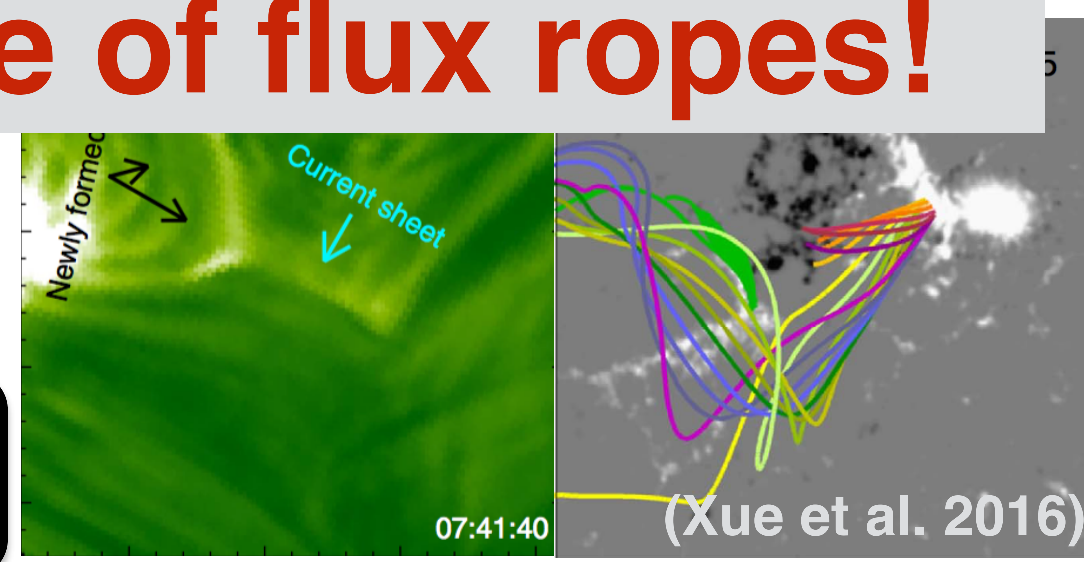


(Guo et al. 2010; Jing et al. 2010; ... b)

No direct evidence of flux ropes!

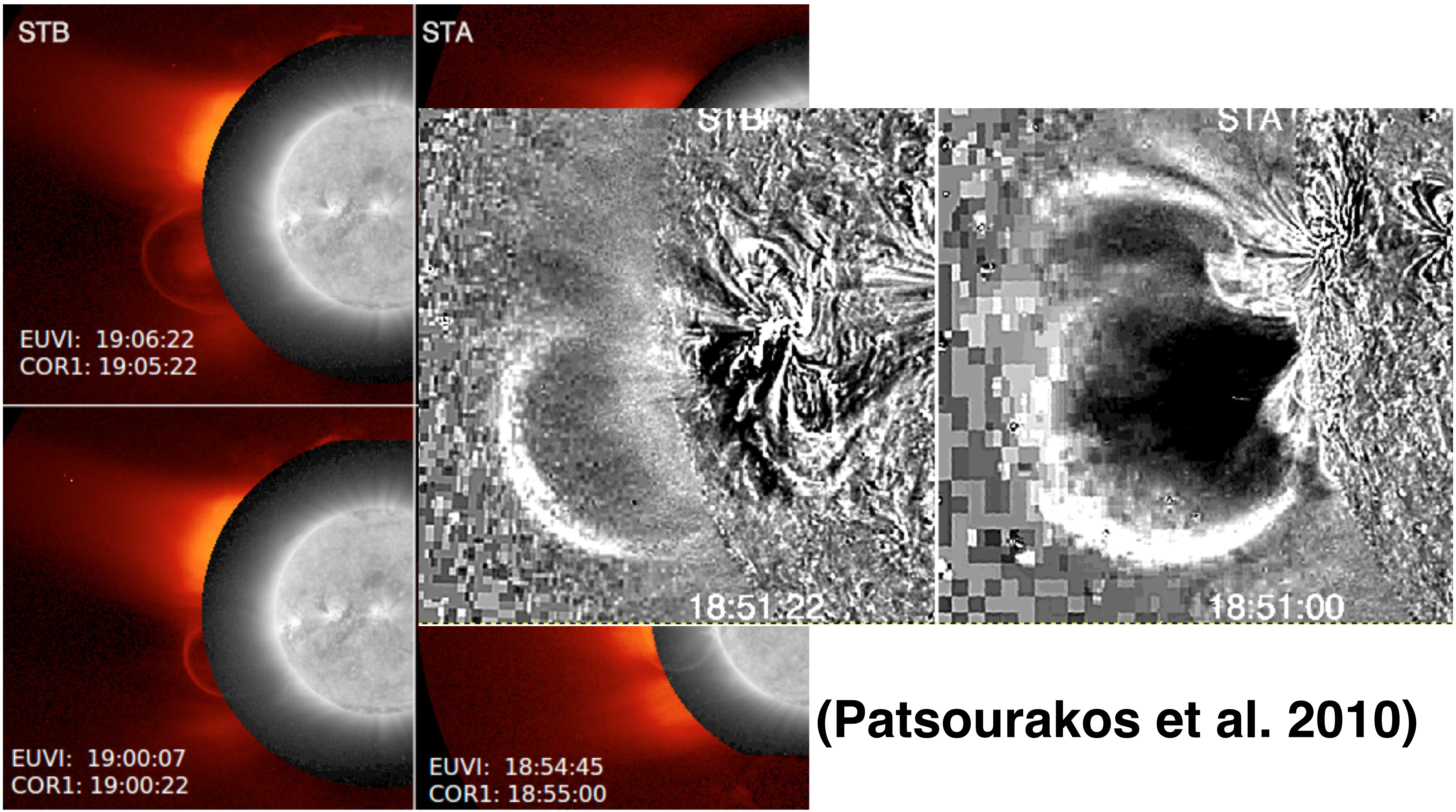
(Gibson et al. 2006; Berger et al. 2012......)

Cavities



(Xue et al. 2016)

CME in the inner corona revealed by STEREO-EUVI

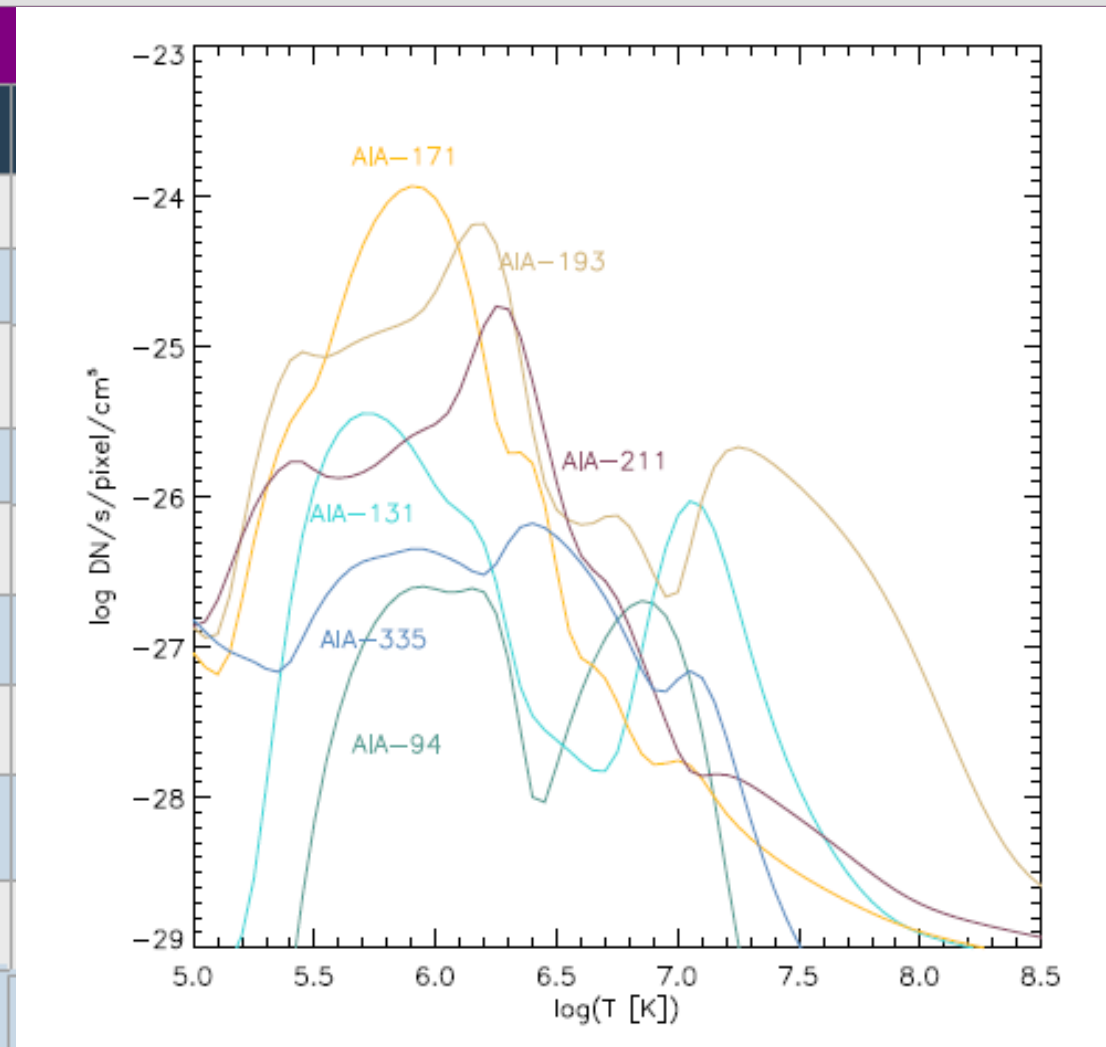


(Patsourakos et al. 2010)

SDO/AIA

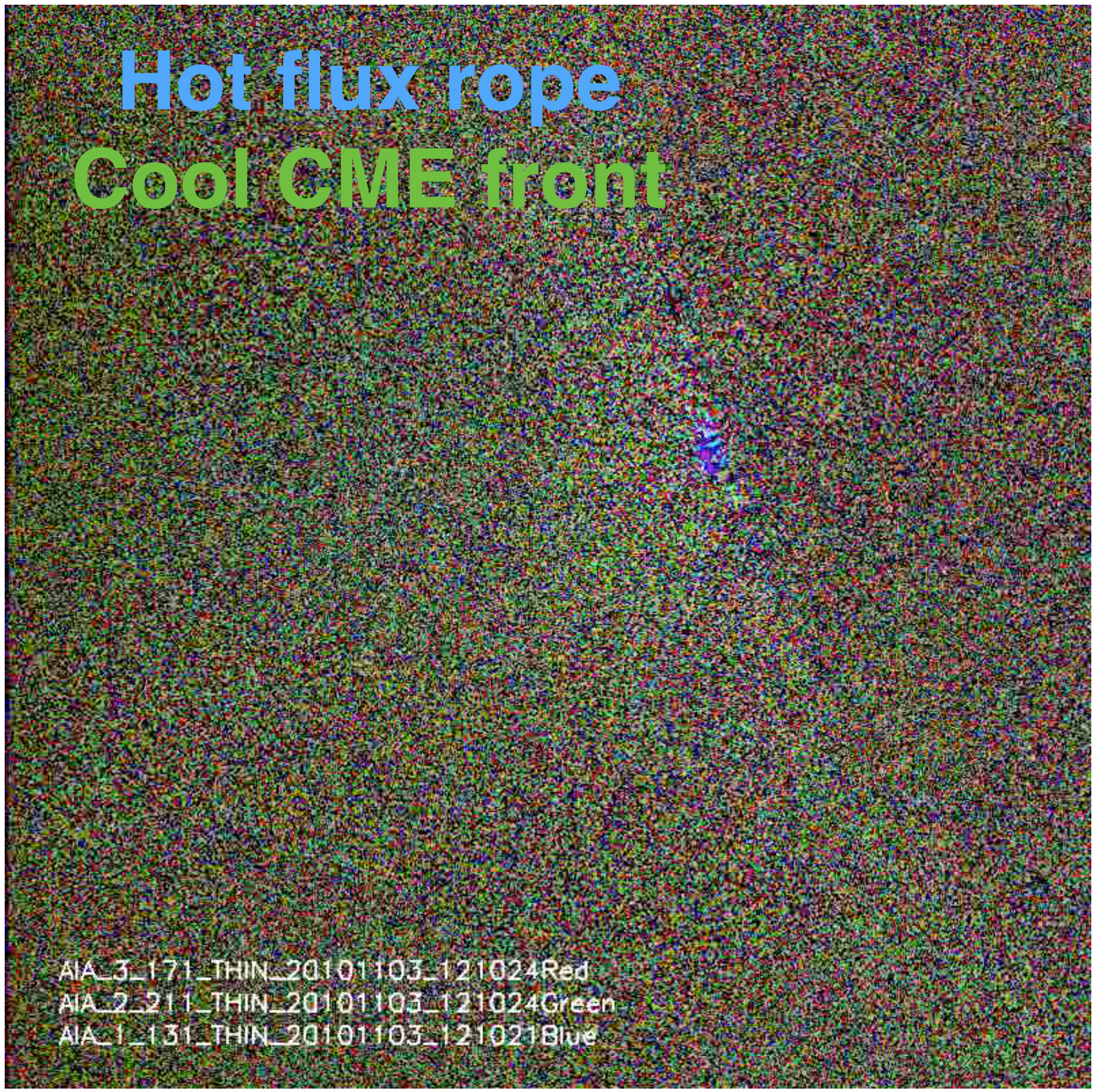
AIA wavelength bands

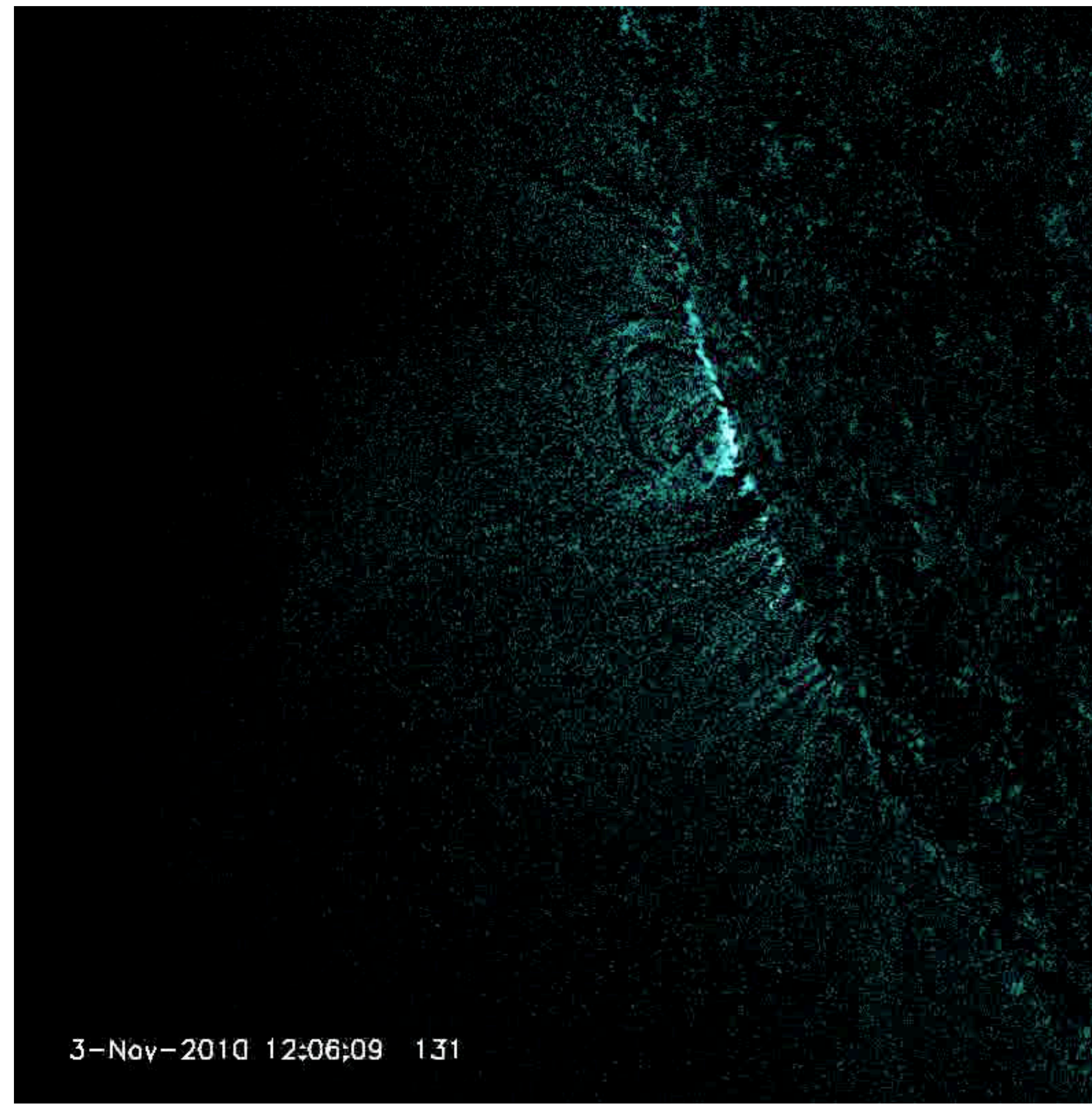
Channel	Δλ††	Ion(s)	Char. log(T)
Visible	-	Continuum	3.7
1700Å	-	Continuum	3.7
304Å	12.7	He II	4.7
1600Å	-	C IV+cont.	5.0
171Å	4.7	Fe IX	5.8
193Å	6.0	Fe XII, XXIV	6.1, 7.3
211Å	7.0	Fe XIV	6.3
335Å	16.5	Fe XVI	6.4
94Å	0.9	Fe XVIII	6.8
131Å	4.4	Fe VIII, XX+	5.7, 7.0, 7.2



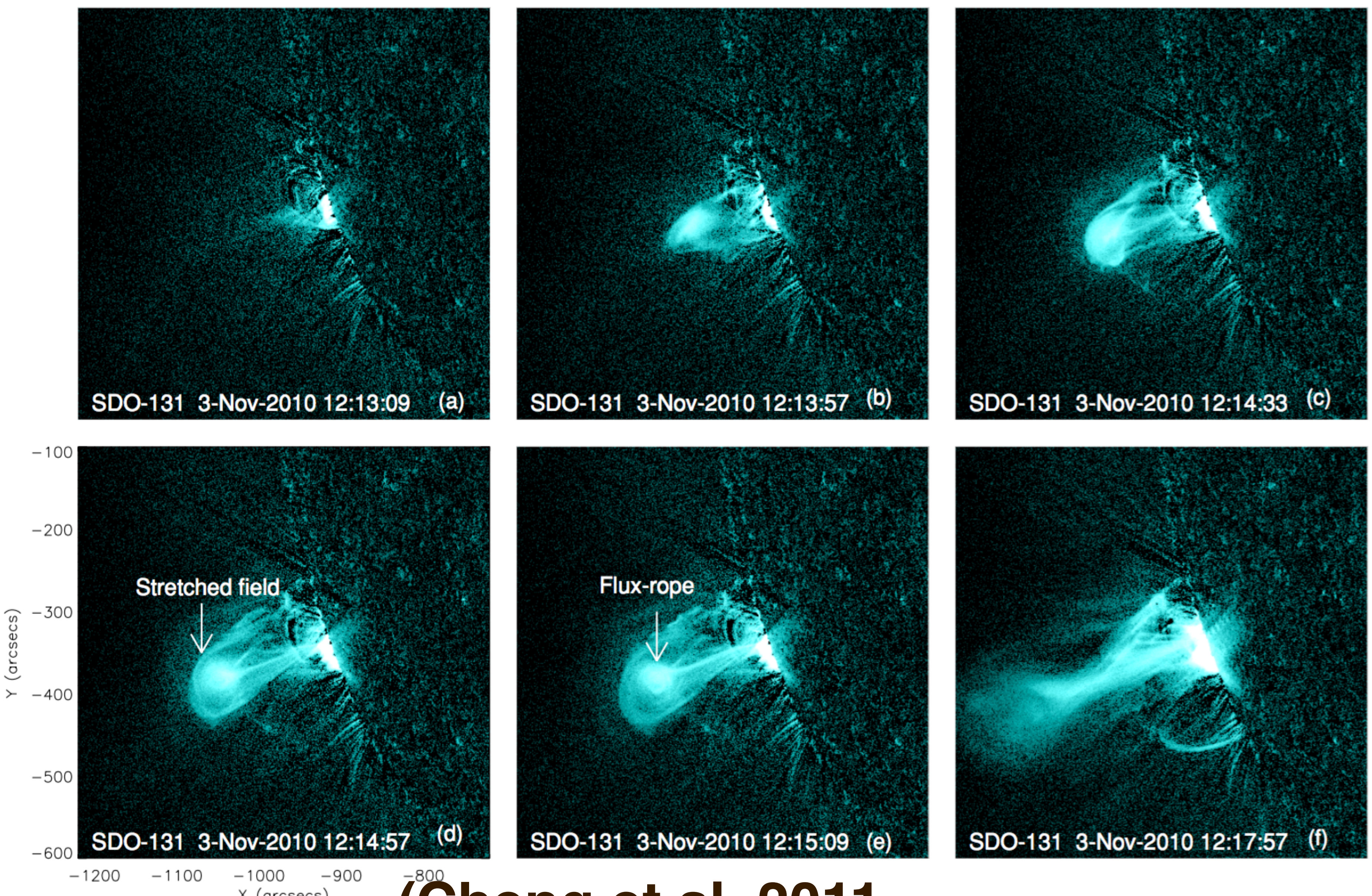
*Absorption allows imaging of chromospheric material within the corona;
††FWHM, in Å

Flux rope and CME

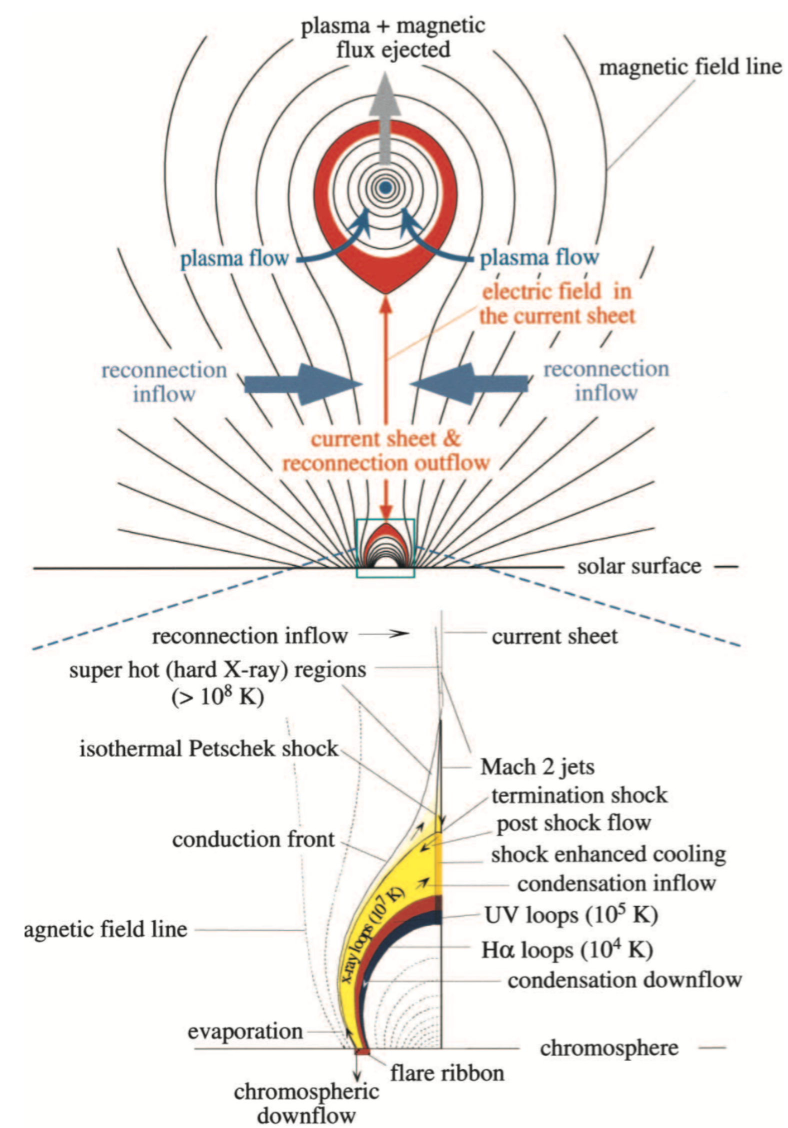




A developing flux rope by reconnection

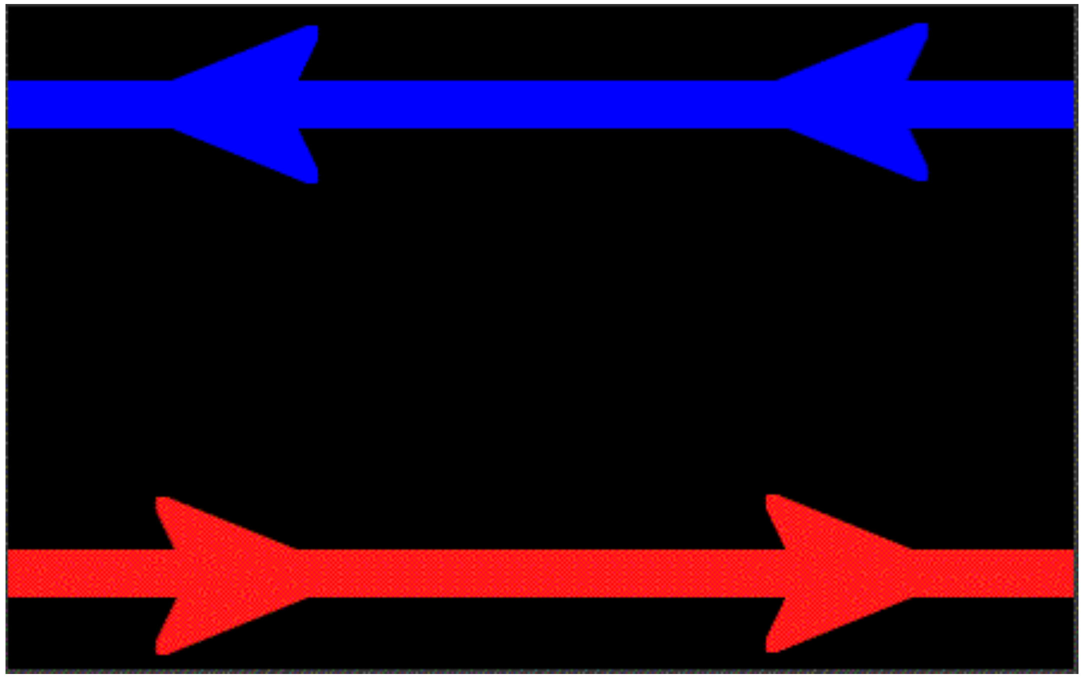


(Cheng et al. 2011, ApJL)



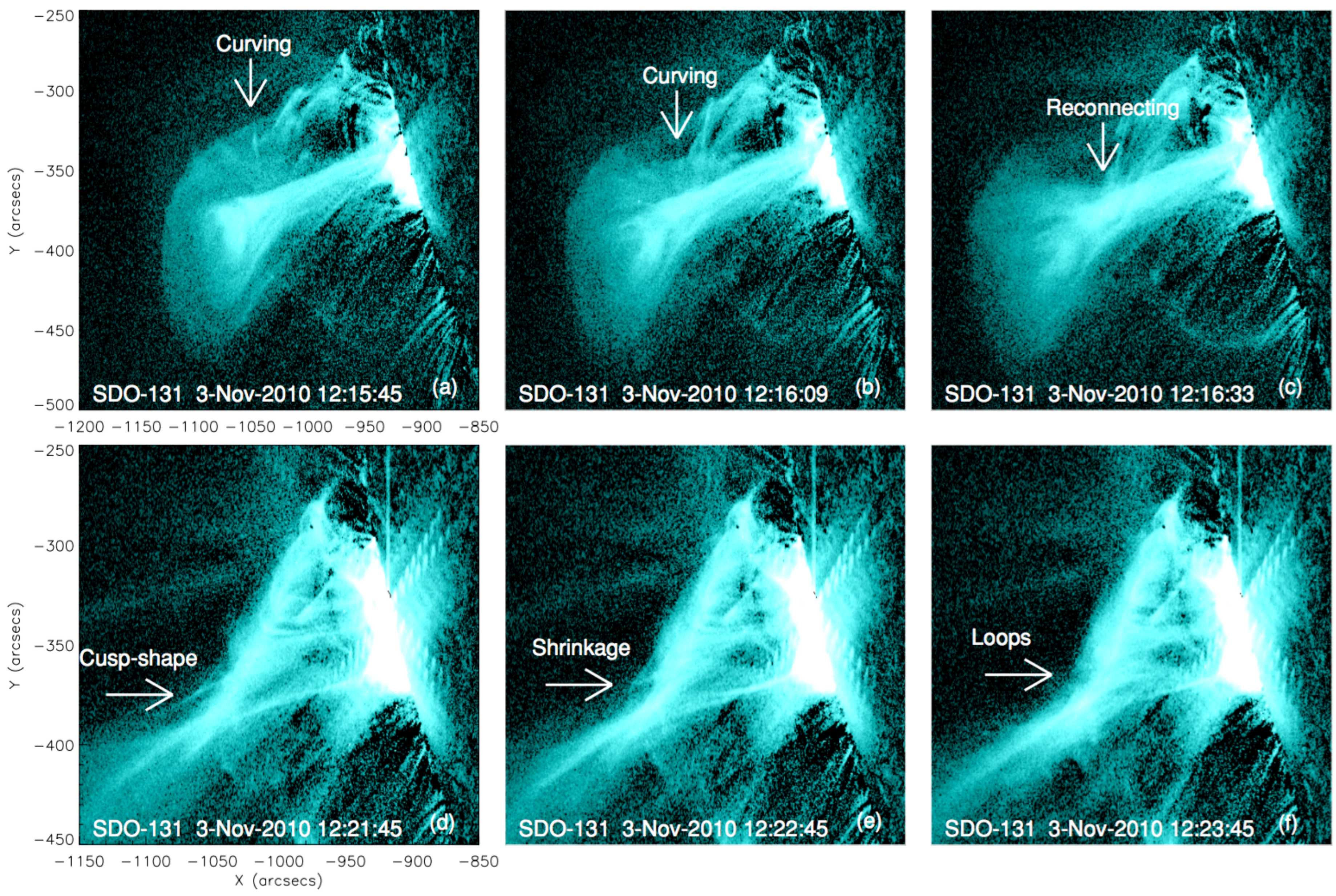
(Lin & Forbes 2000)

Evidence of reconnection

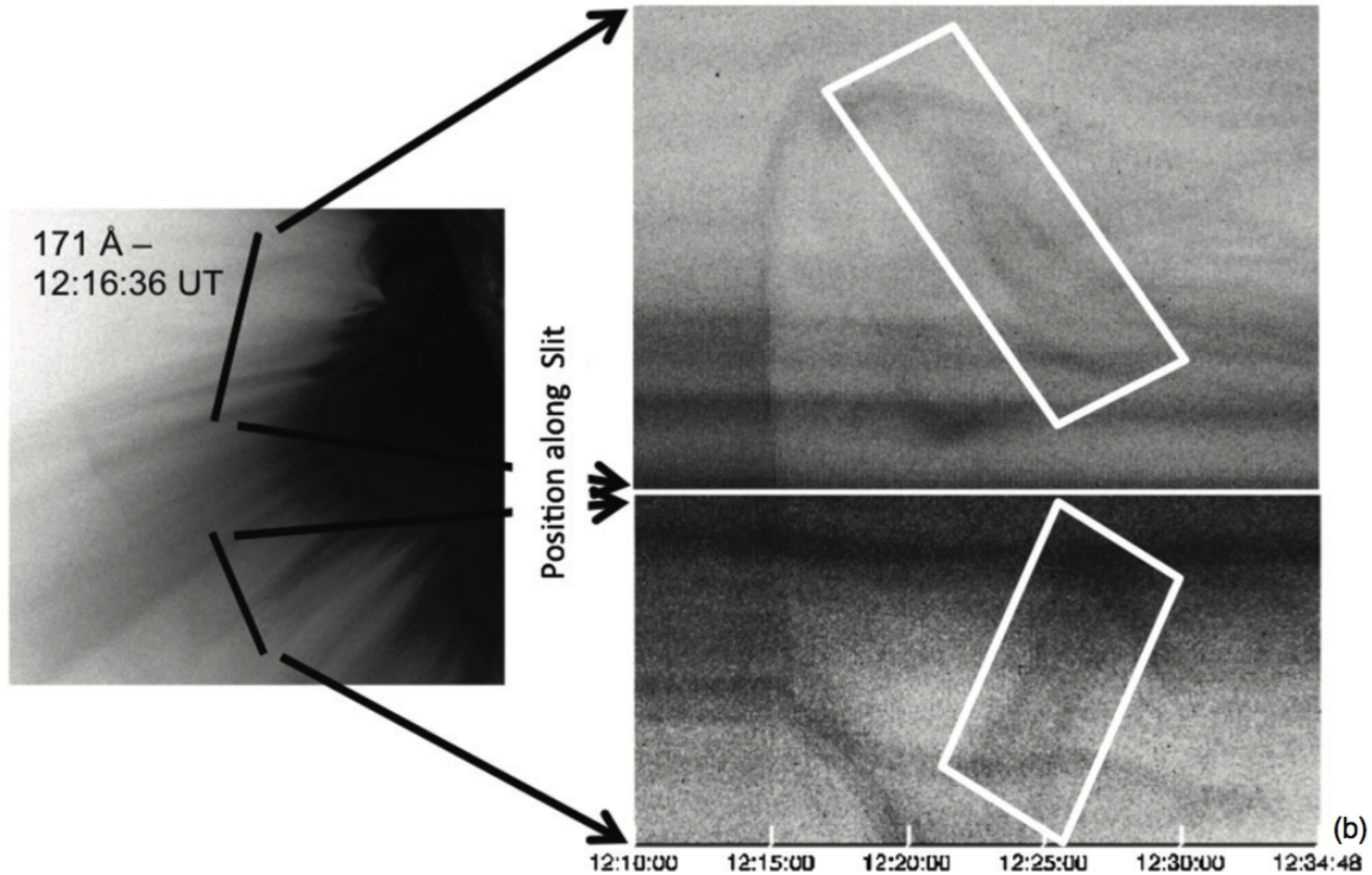


1. Moving to the current sheet: evidence of inflows

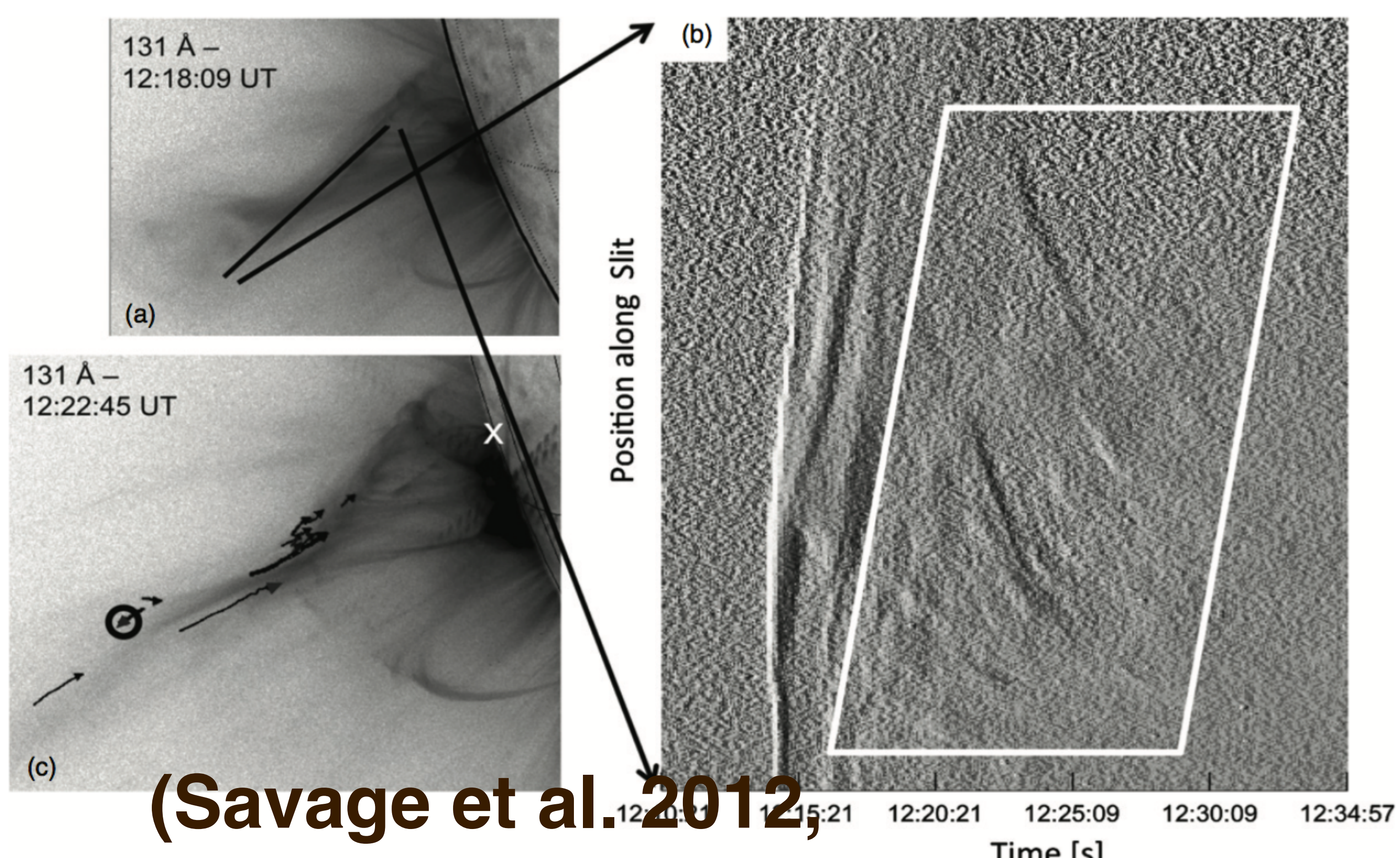
2.Shrinking from cusp-shape to semicircular shape



Inflows:

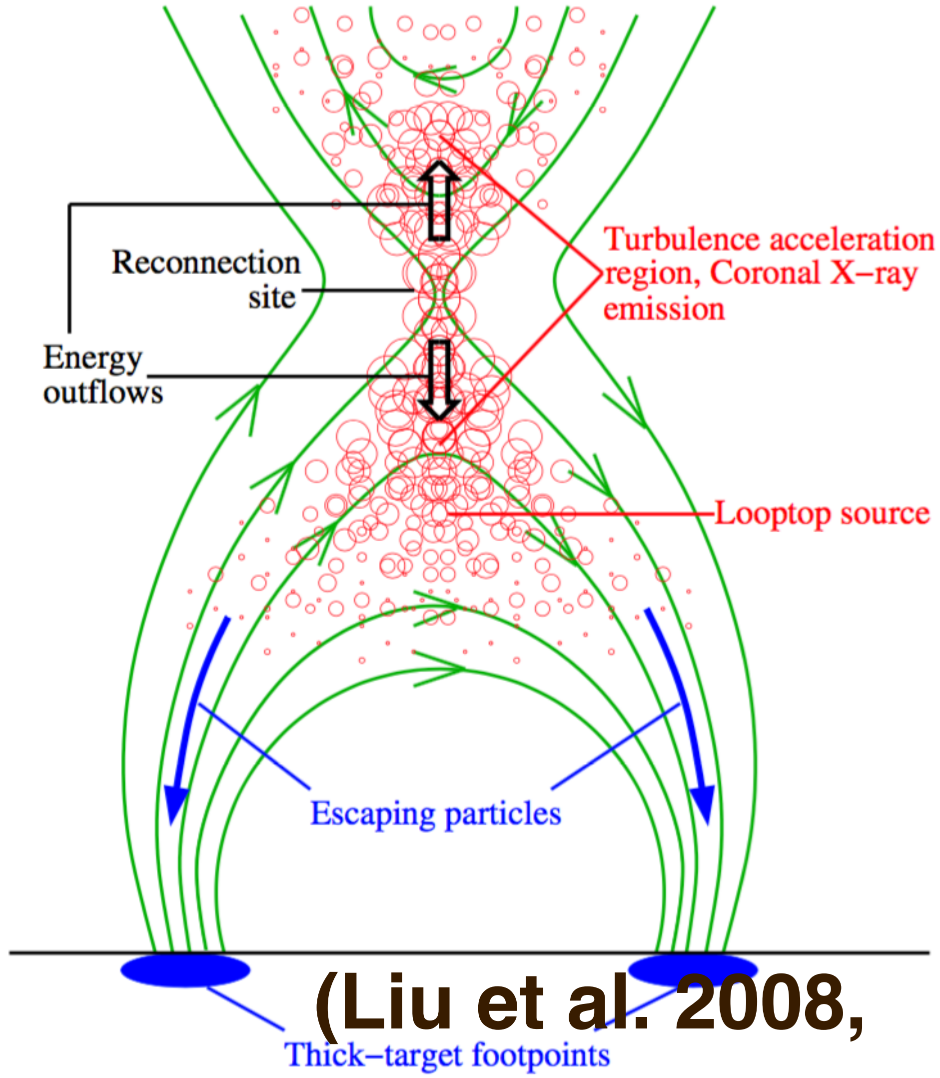


Downflows:

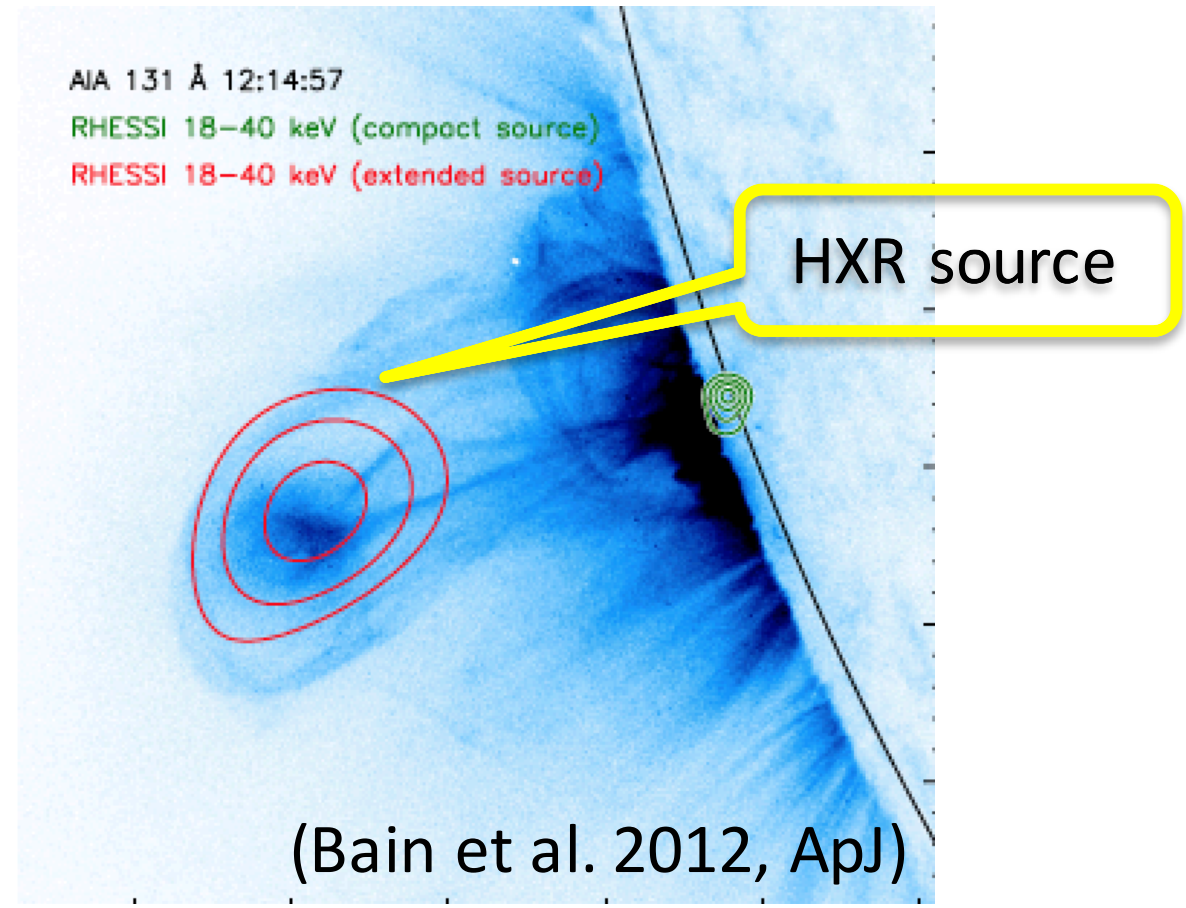


(Savage et al. 2012, ApJ)

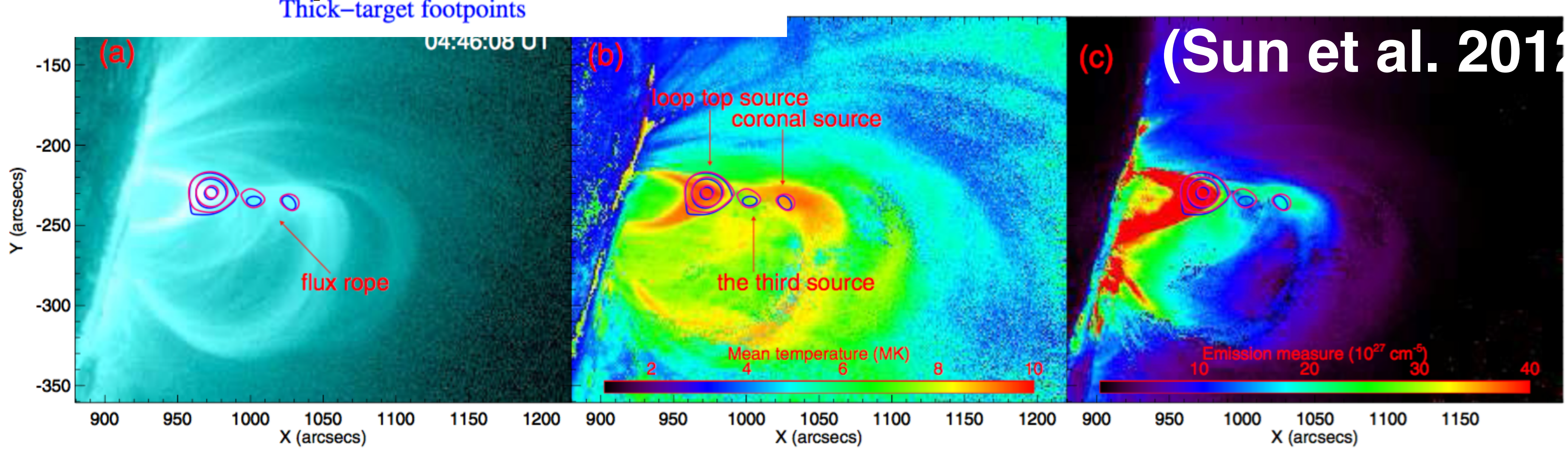
Particles acceleration and Hard X-ray sources



(Liu et al. 2008,



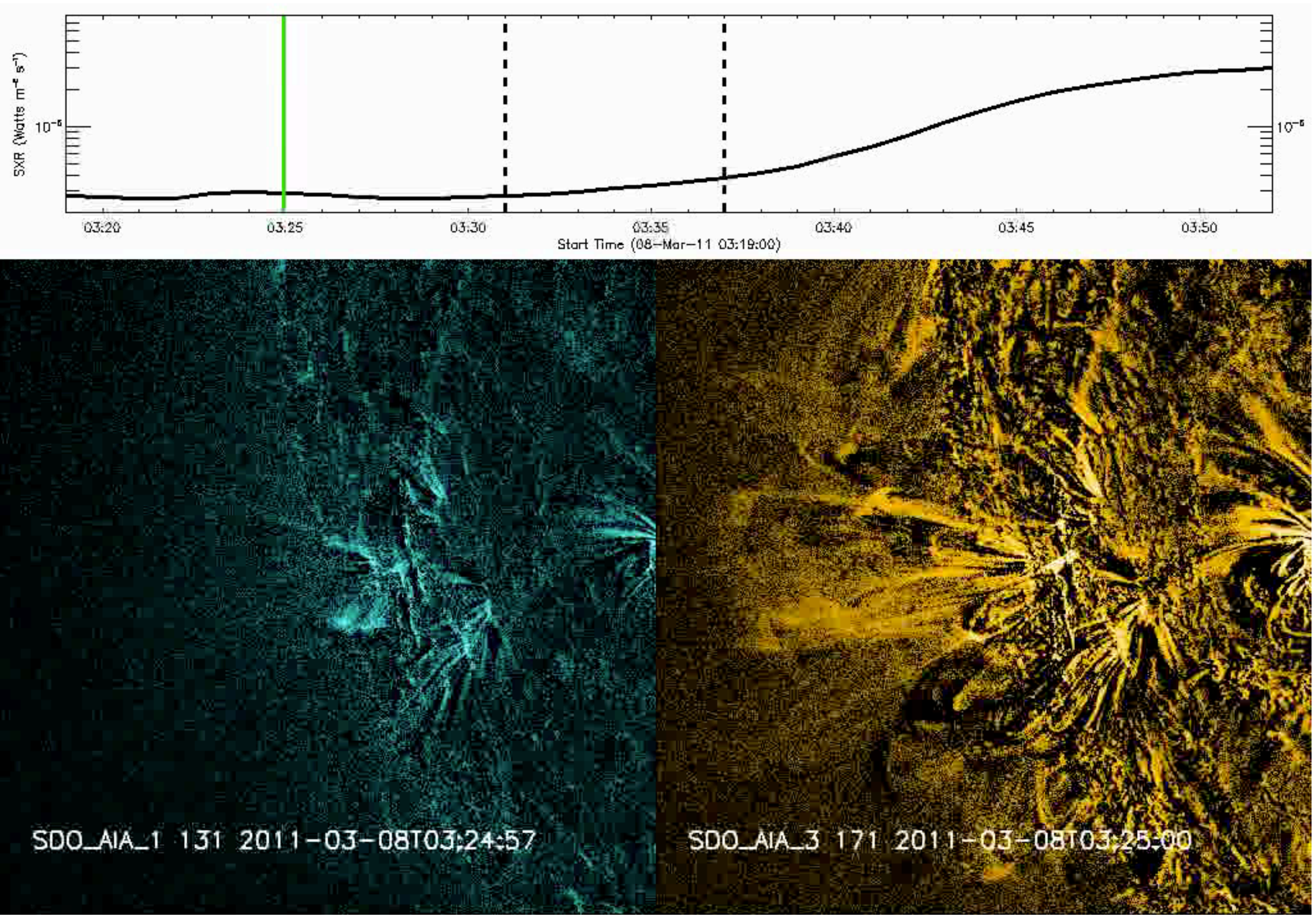
(Bain et al. 2012, ApJ)



(Sun et al. 201

Evidence of the MFR existing prior to the eruption

EUV Hot Channel!



1. Appearing as a channel-like structure with a high temperature of >7MK,

2. Appearing in the dark cavity, following a bright front,

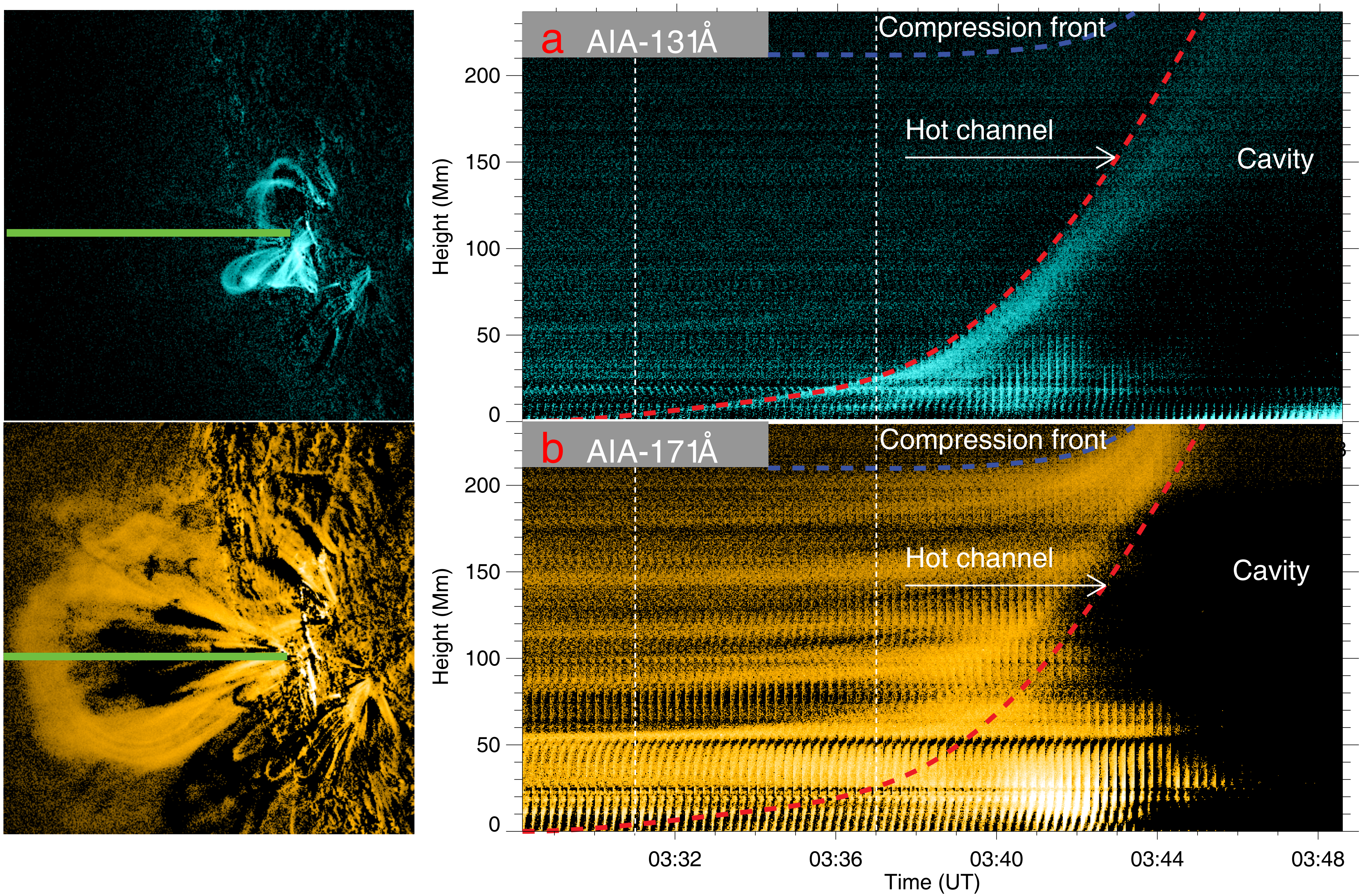
3. Existing prior to the first appearance of the CME,

4. Evolving from S-shape to semicircle,

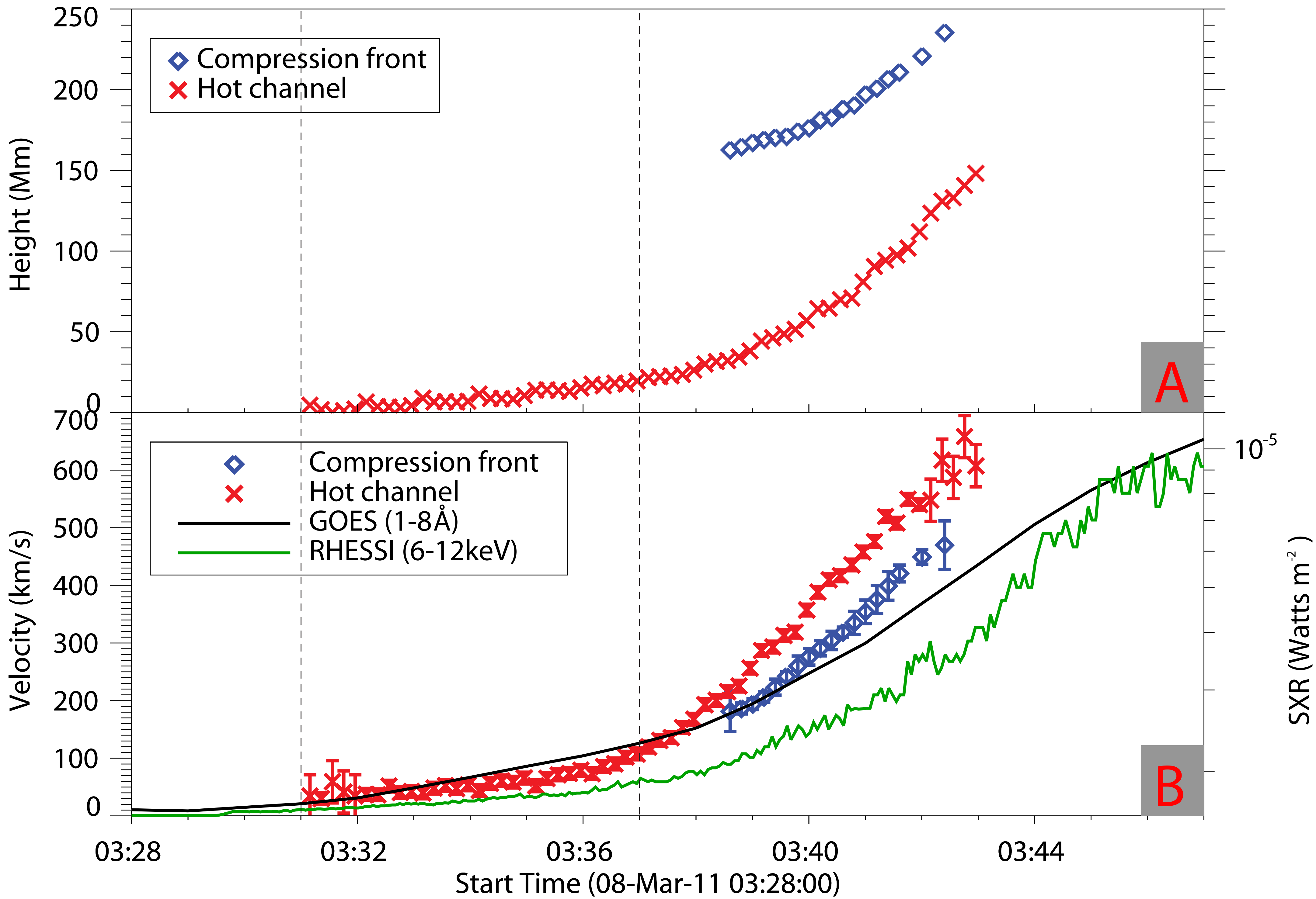
5. With fixed footpoints.

(Zhang, Cheng & Ding 2012; Cheng et al. 2013a, 2014a)

Role of MFR in forming and accelerating CME



Role of MFR in forming and accelerating CME

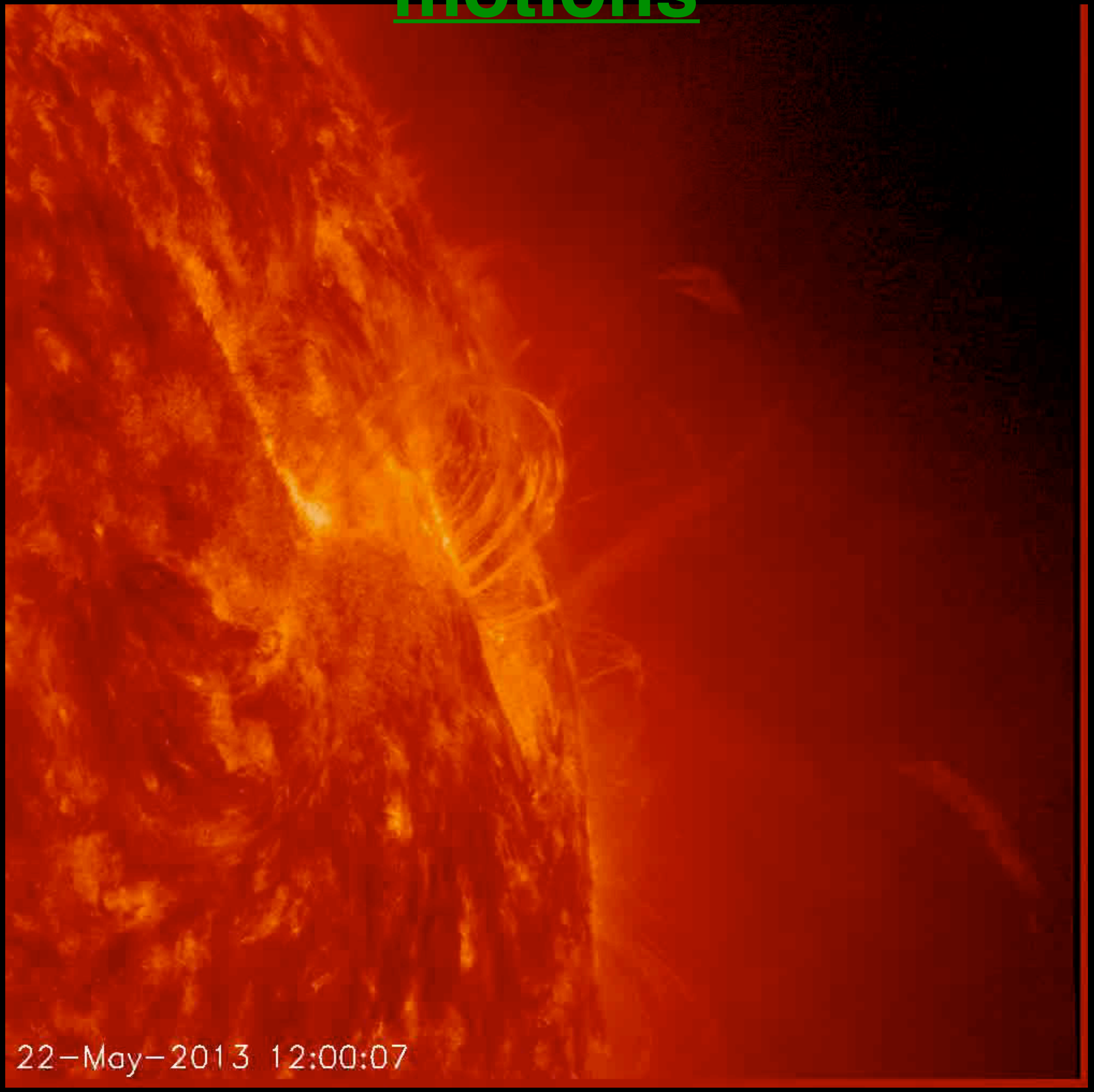


(Zhang, Cheng & Ding 2012; Cheng et al. 2013a, 2014a)

Helical threads inside the MFR

Rotational descending motions

22−May−2013 12:00:08.640



(Cheng et al. 2014a, Li et al. 2013, Zhang et al. 2015)

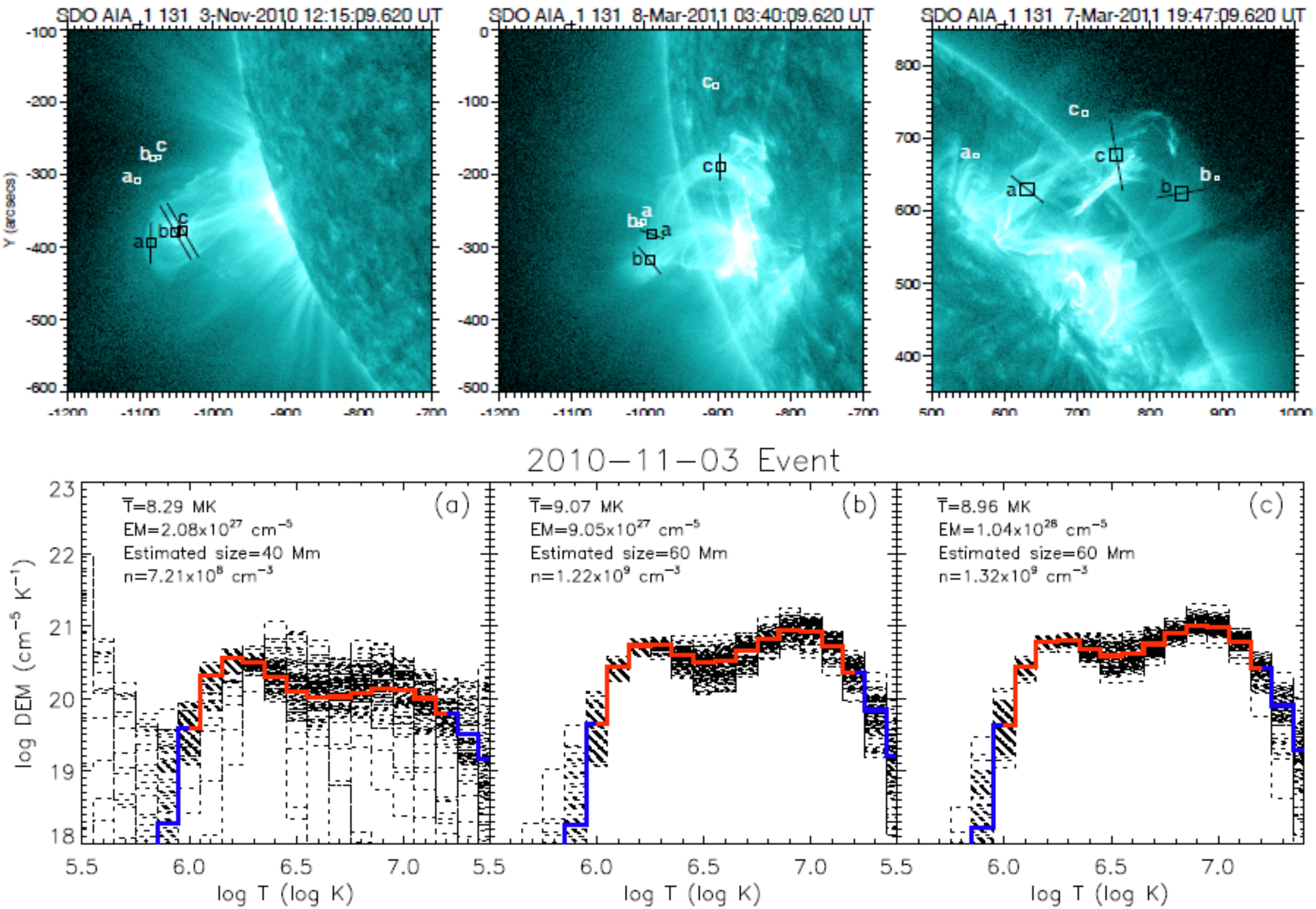
Differential Emission Measure Determination

Method: Iterative

$$F_i = \int R_i(T) \times \mathrm{DEM}(T)\, dT,$$

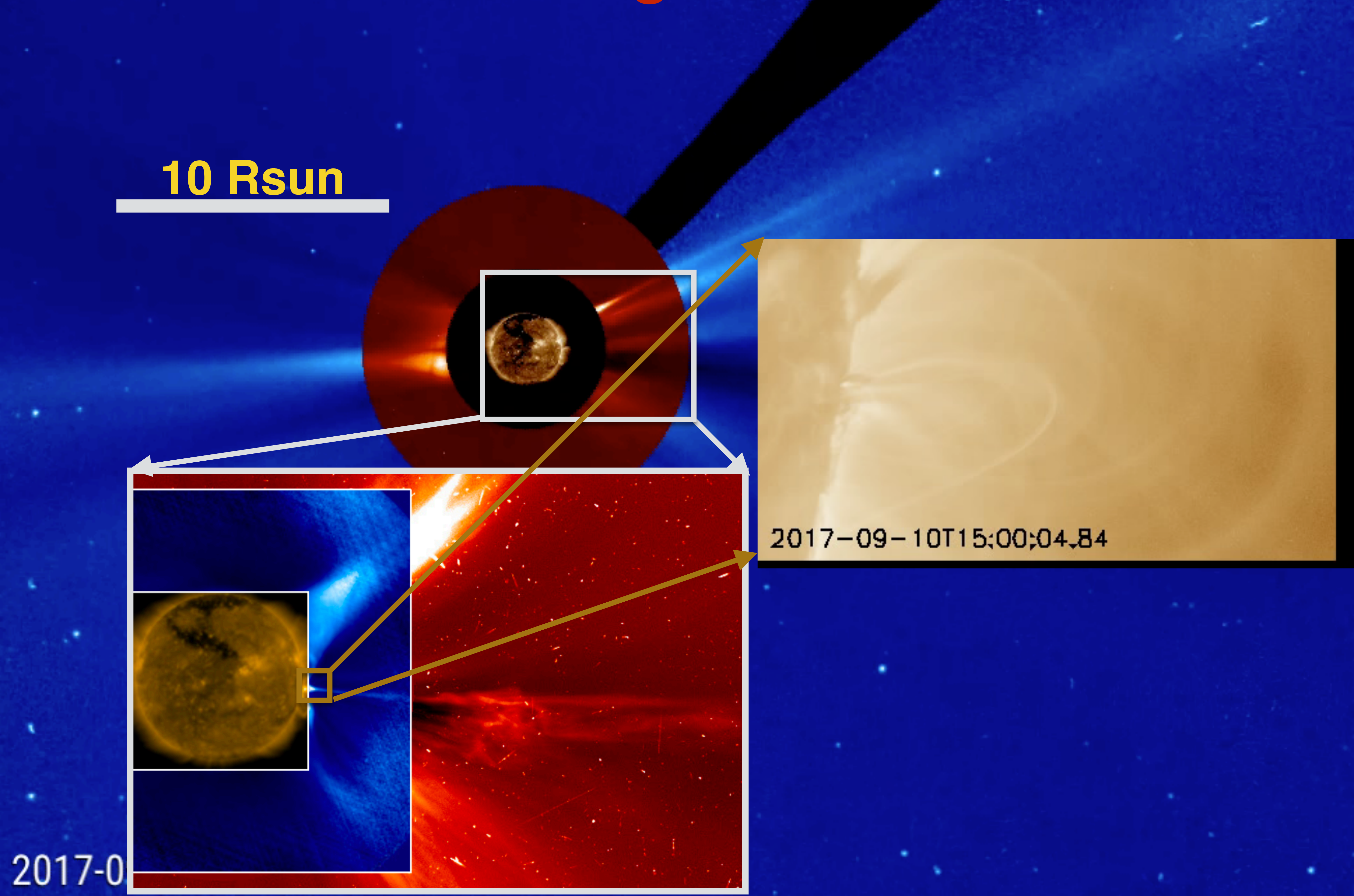
We assume a starting DEM that apply for above function, and compare the predicted observations with the real observations for each filter.
The optimal DEM spline is found using IDL mpfit routines, which search towards a minimum *χ2*

DEM structure of MFR



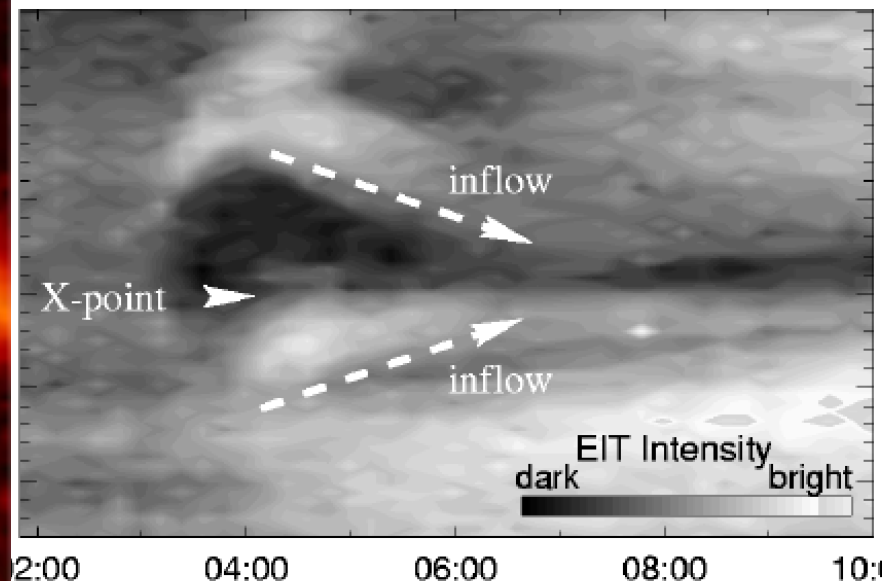
(Cheng et al. 2012)

CME induced magnetic reconnection

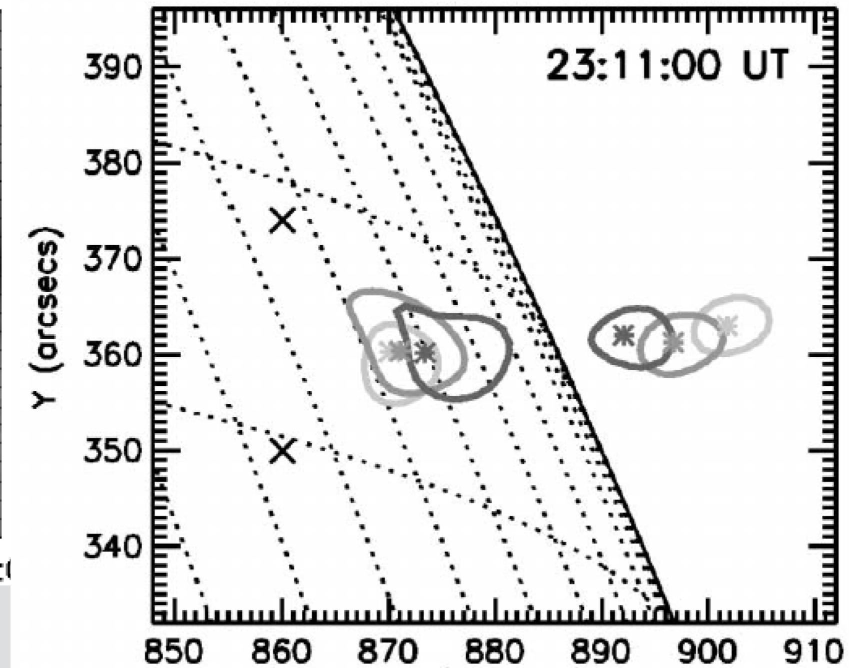


Evidence for reconnection during CME/flare

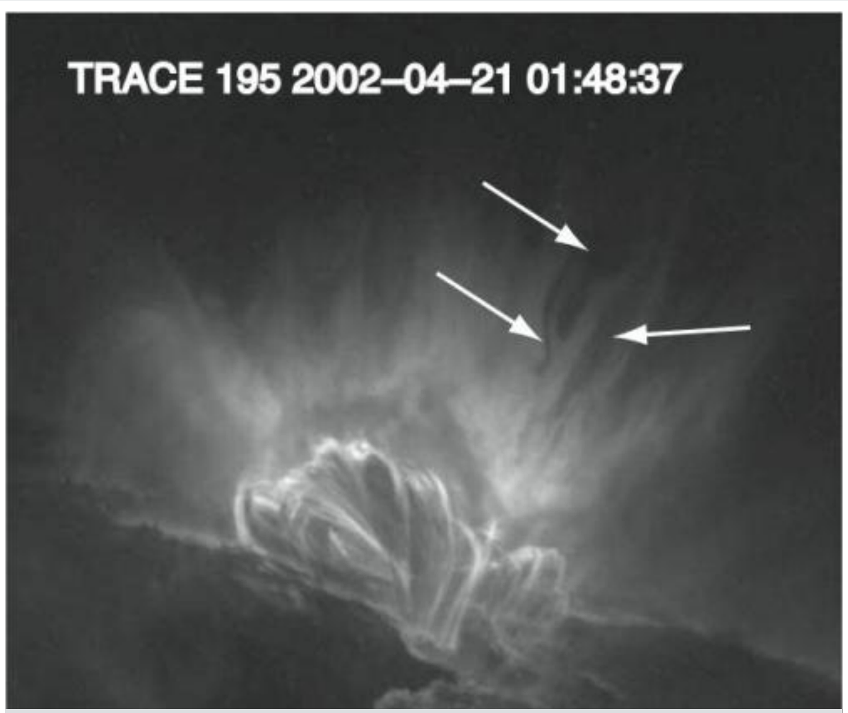
Masuda et al. 1994



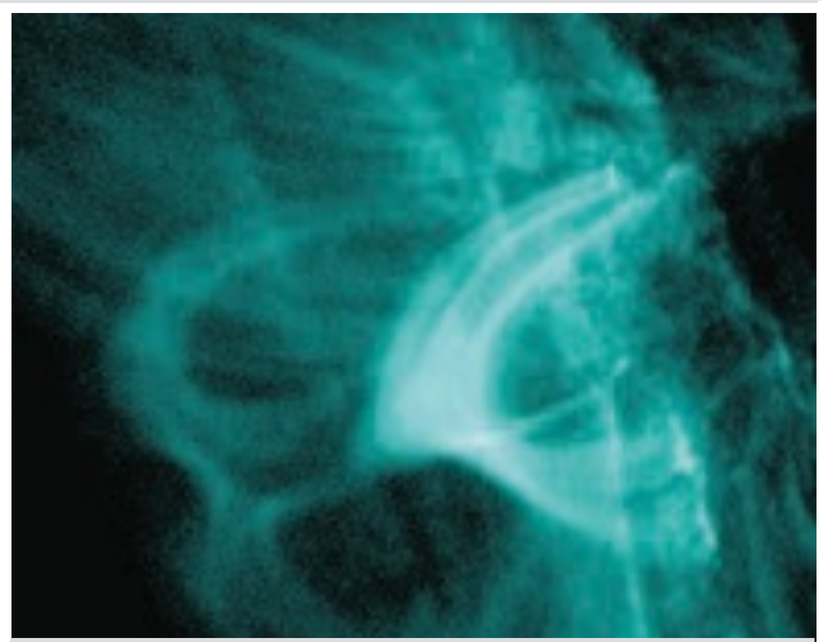
Yokoyama et al. 2001
Li et al. 2009



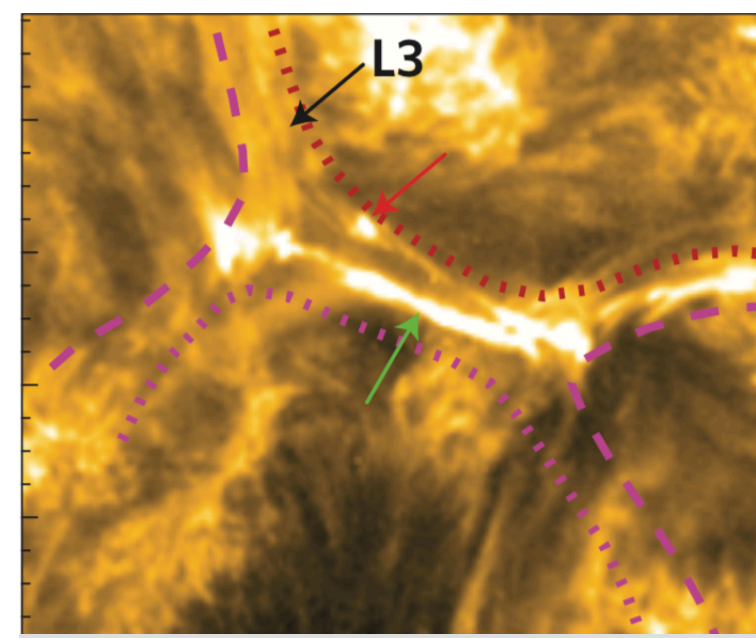
Sui et al. 2003



McKenzie et al. 2009

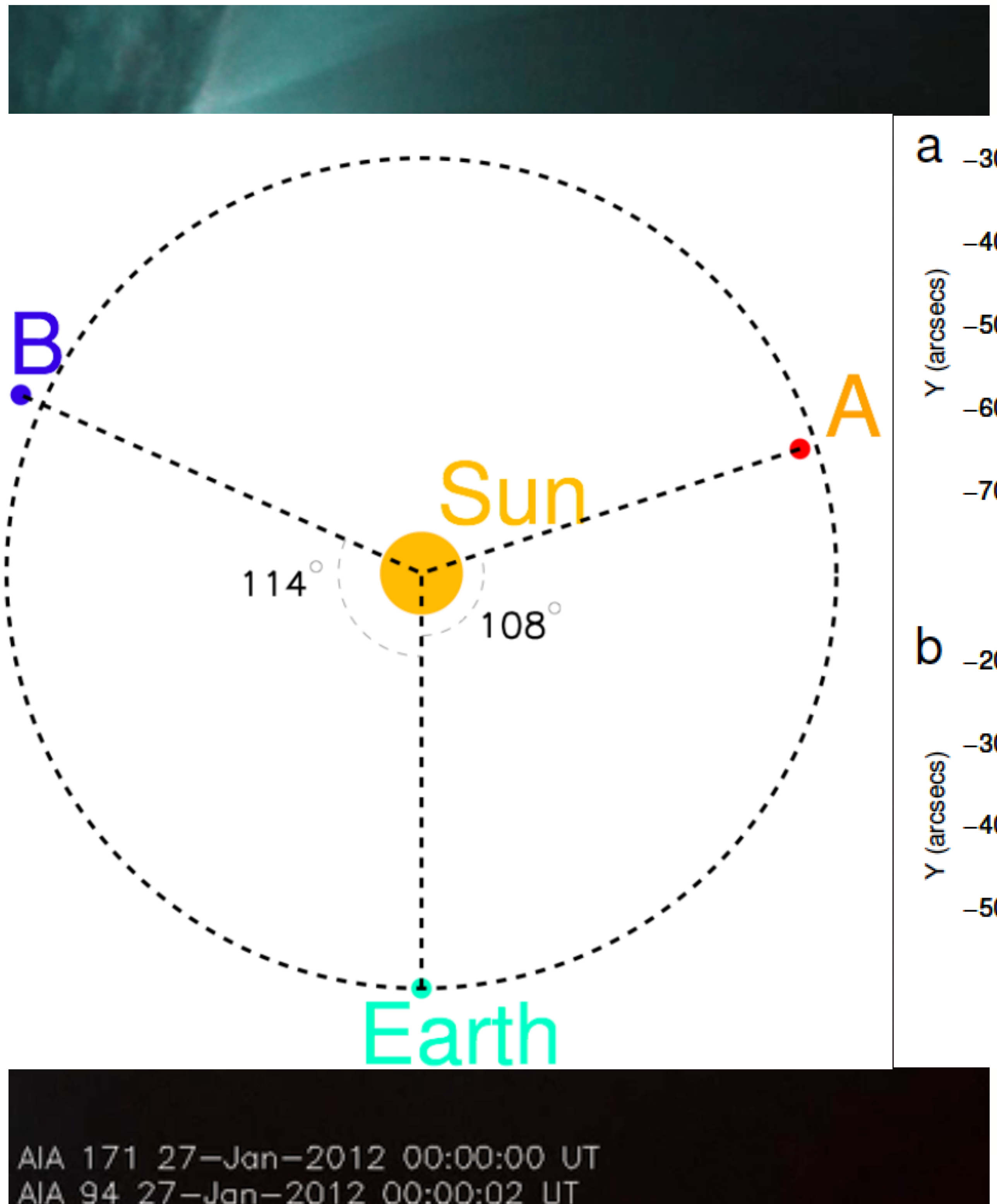


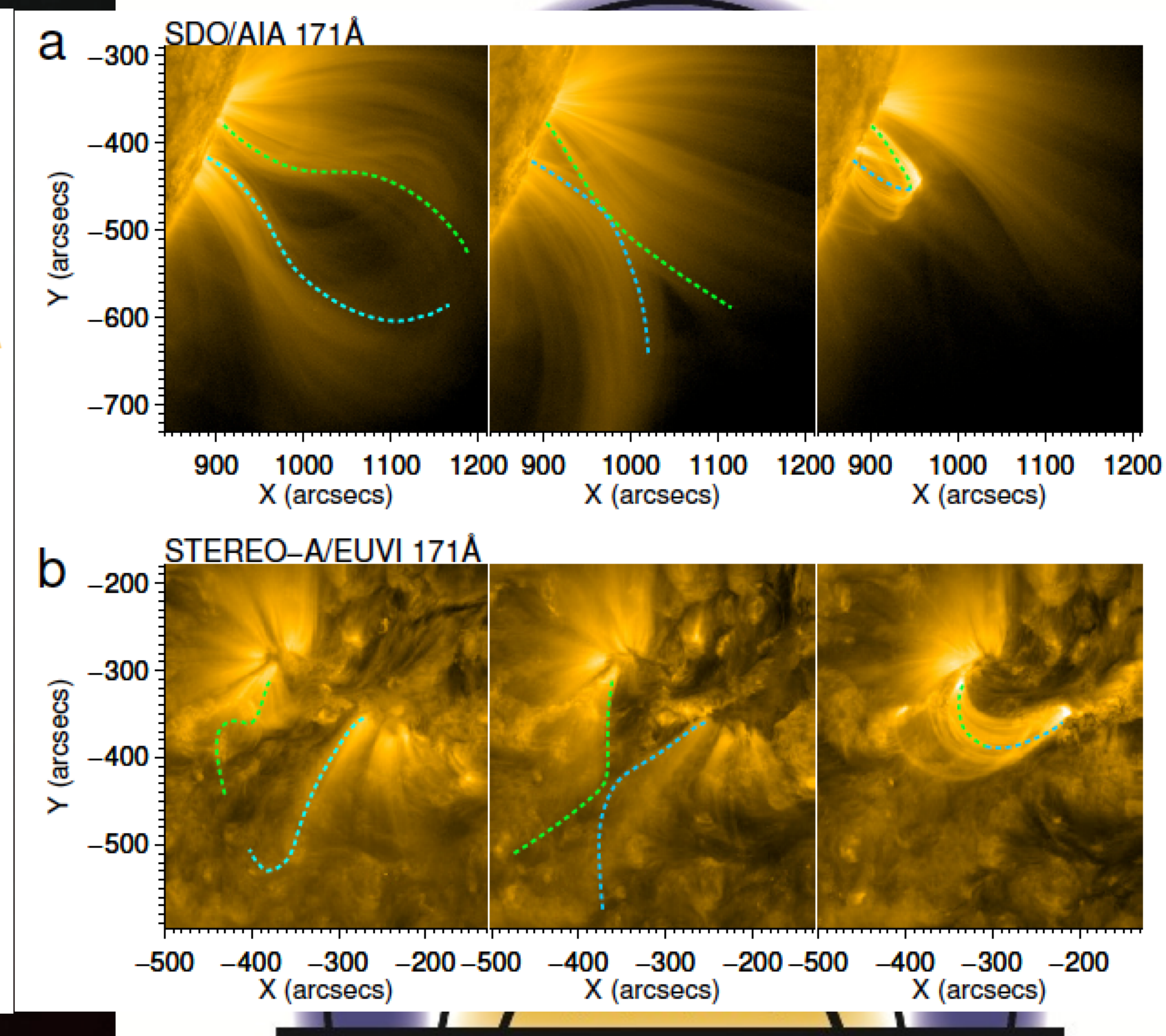
Su et al. 2013,
Yang et al. 2014



Li et al. 2016,
Xue et al. 2017

3D imaging of magnetic reconnection caused by the flux rope eruption

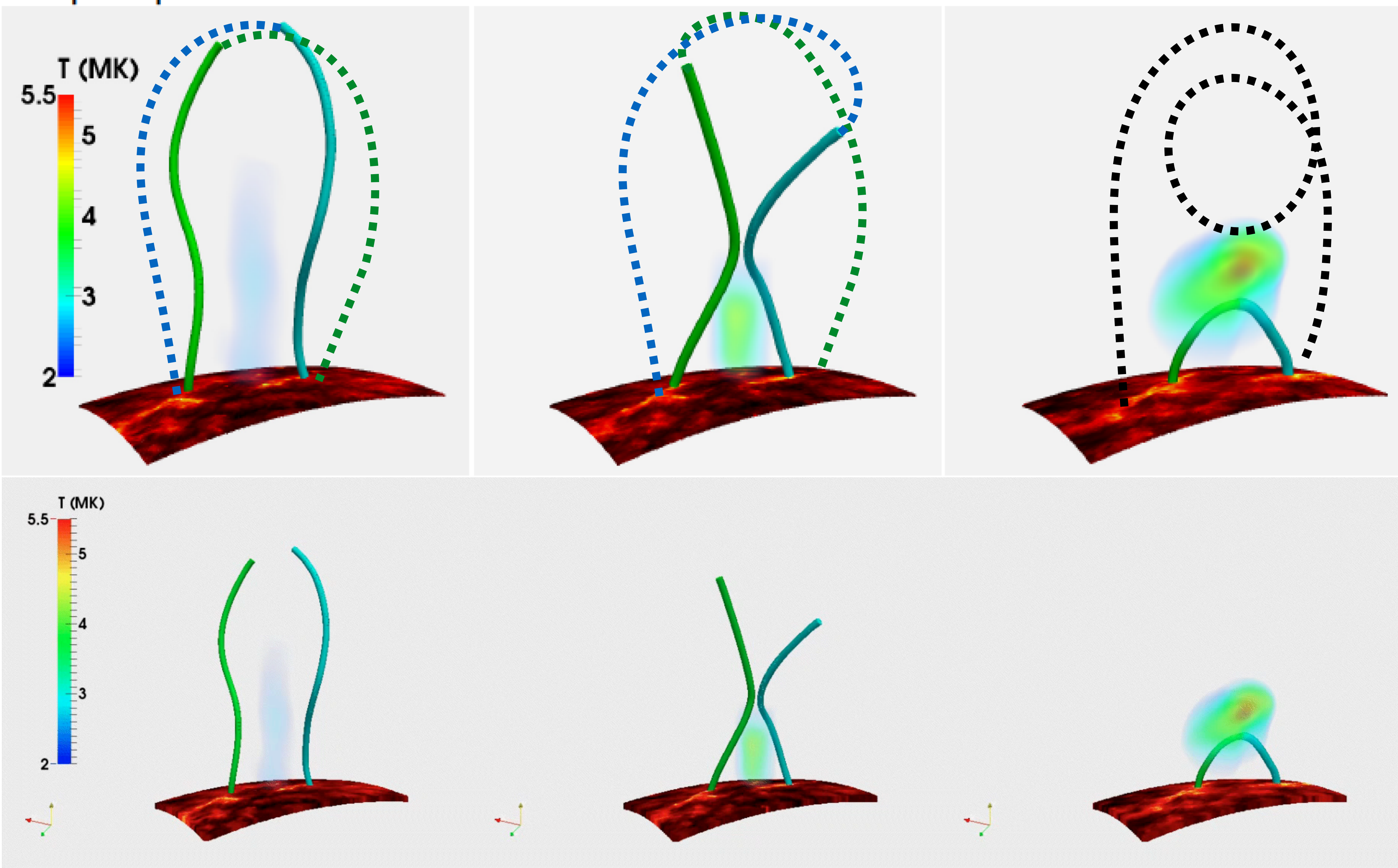




(Cheng et al. 2011b)

3D topology of reconnecting magnetic loops and heated plasma

3D perspective



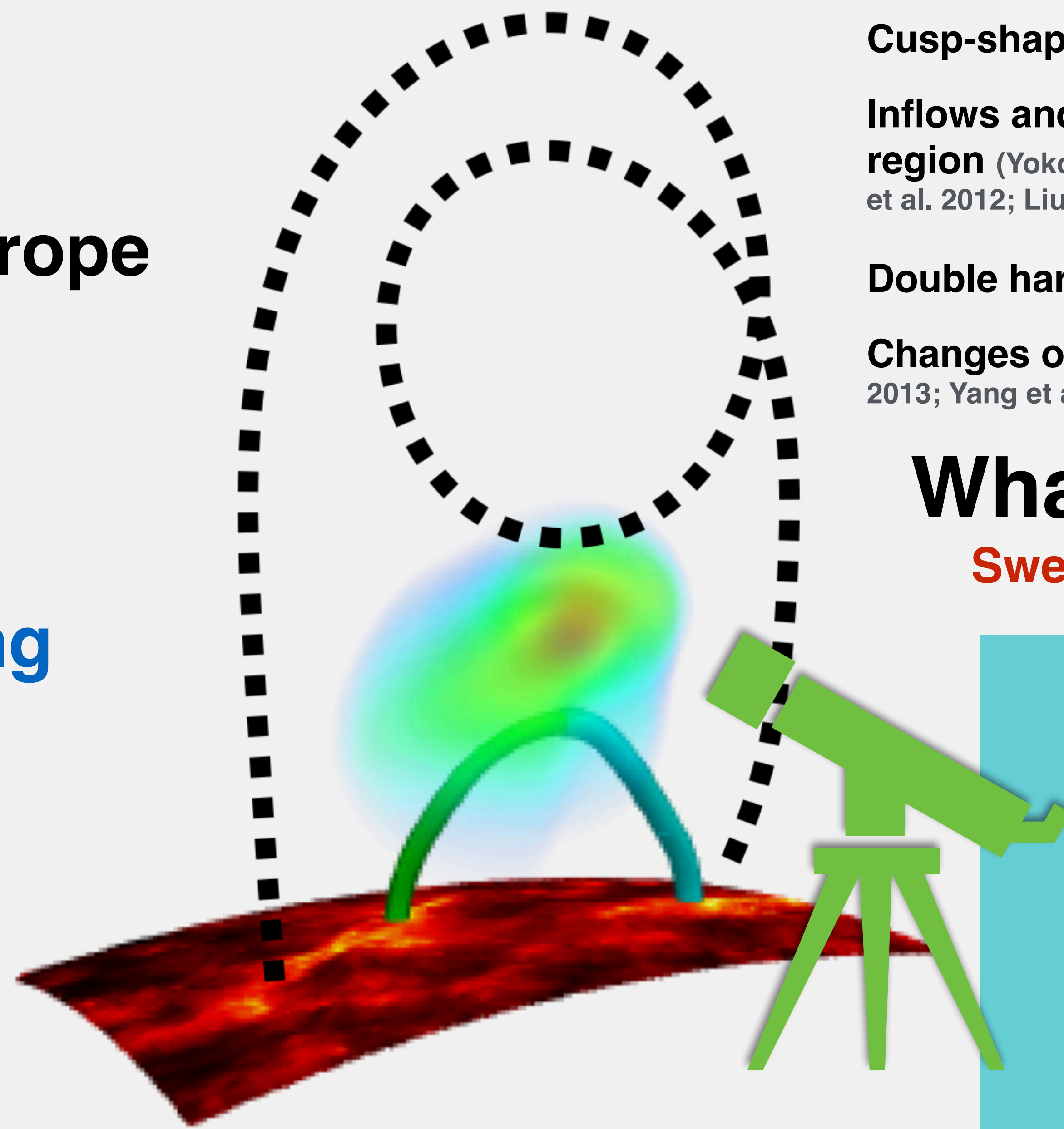
3D structure of Solar Eruption

Erupting flux rope

Reconnection
Plasma heating

Flare loops

Flare ribbons



(Sun, Cheng et al. 2015)

Cusp-shaped flare loops (Masuda et al. 1994);

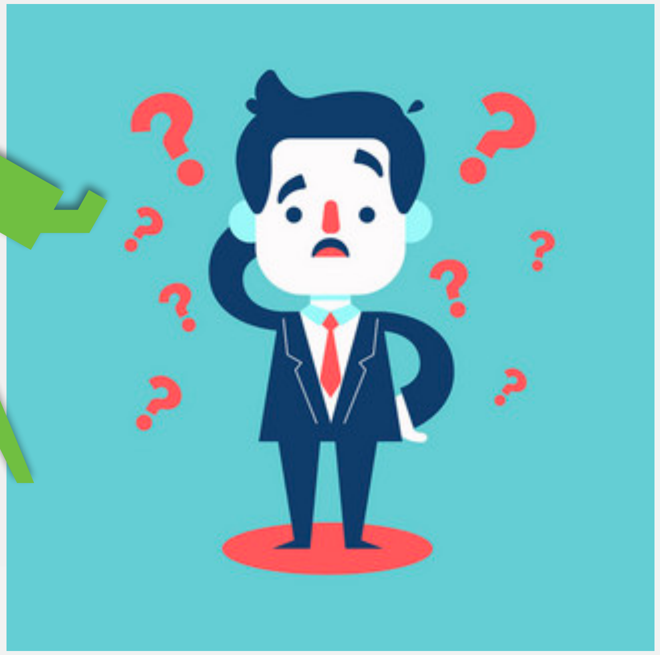
Inflows and downflows near the reconnection region (Yokoyama et al. 2001; Savage & McKenzie 2011; Takasao et al. 2012; Liu et al. 2013; Xue et al. 2016)

Double hard X-ray coronal sources (Su et al. 2003);

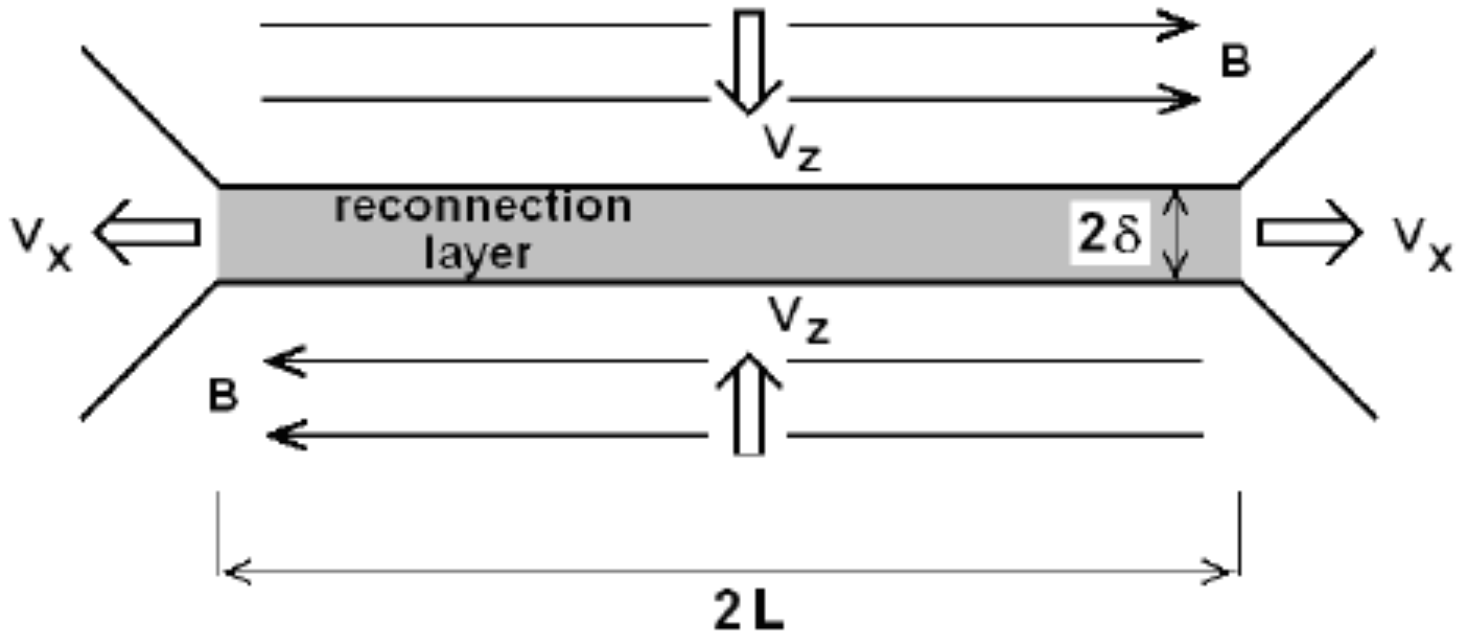
Changes of connectivity of coronal loops (Su et al. 2013; Yang et al. 2015; Li et al. 2016).

What happens here

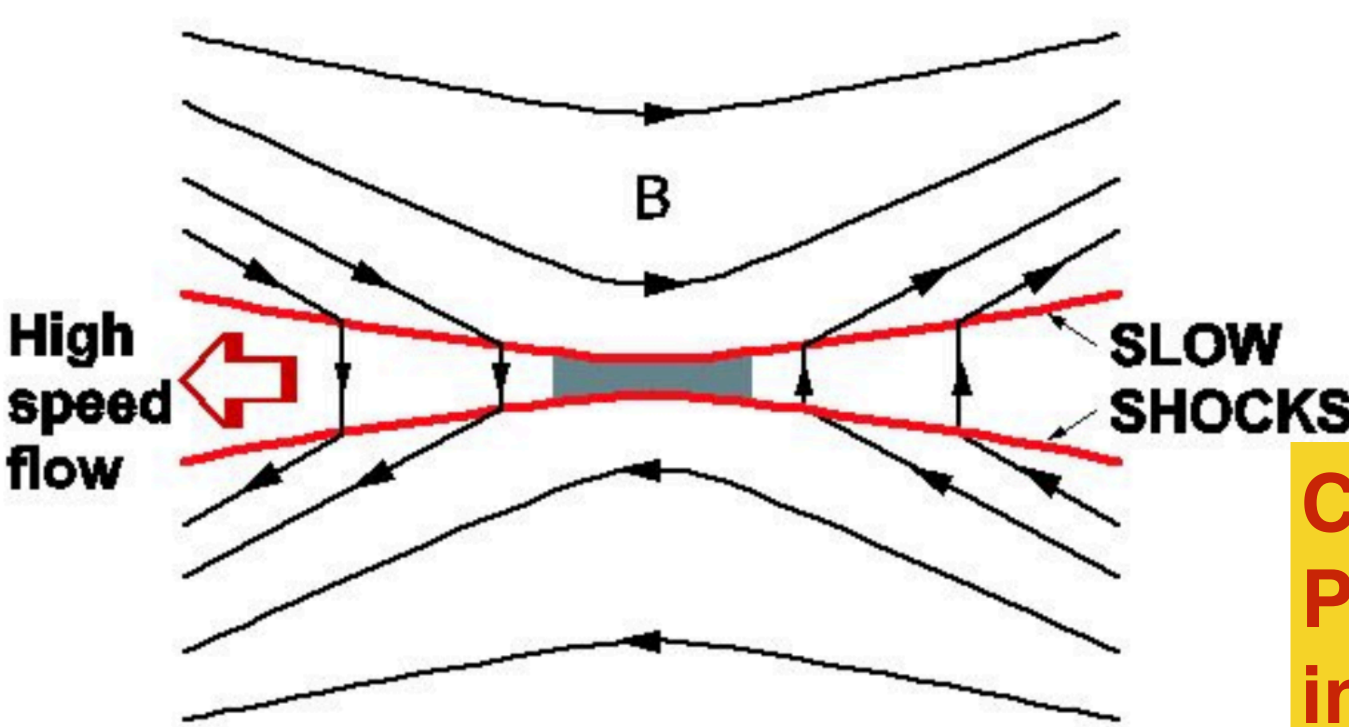
Sweet-Parker and Petschek?



Sweet-parker and Petschek model



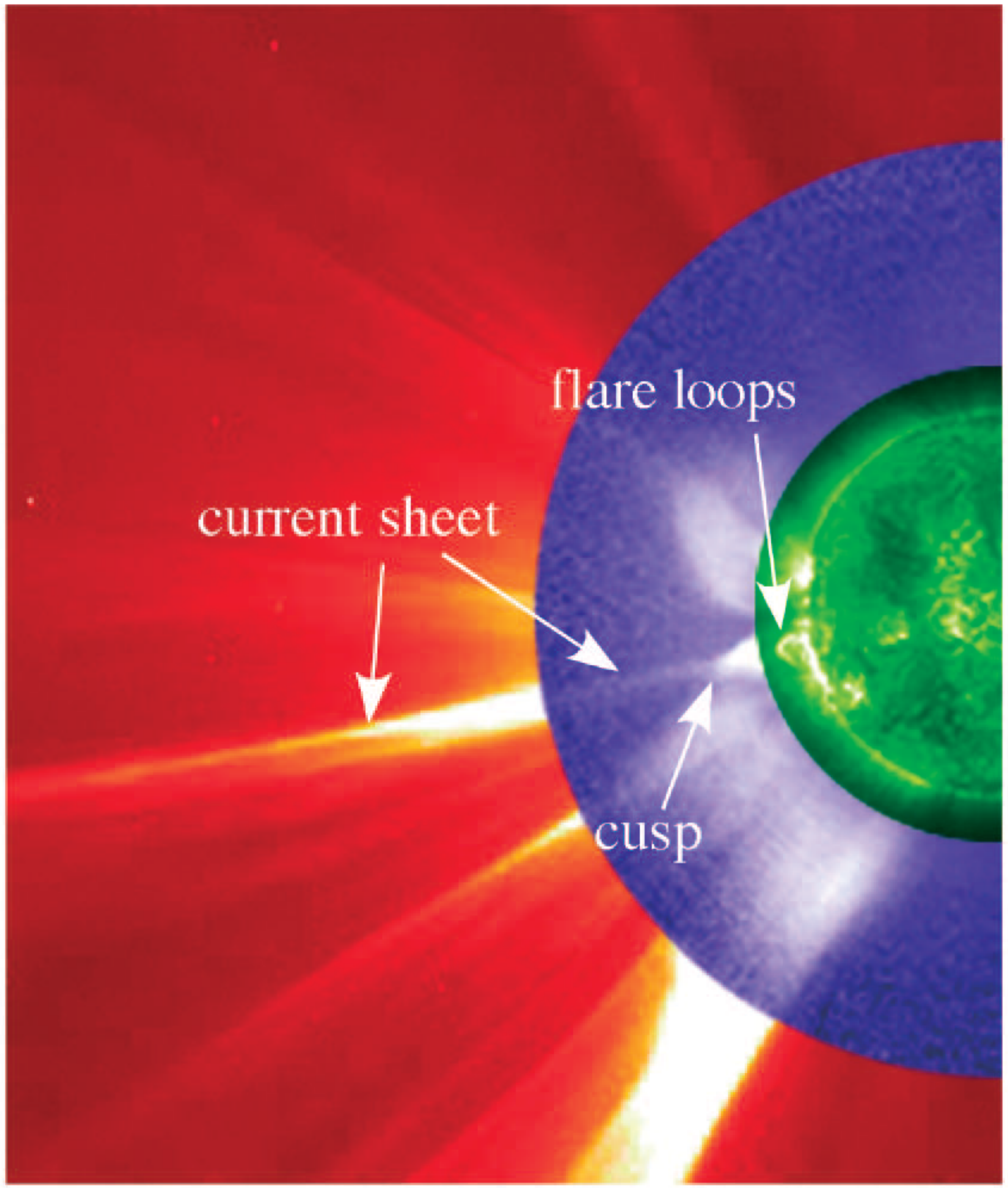
$$M_A \sim R_m^{-1/2}$$
$$\sim (10^{-14})^{-1/2}$$
$$\sim 10^{-7}$$



$$M_A \sim 1/\ln R_m$$
$$\sim 0.1$$

Current sheet width in the Petschek model is of ion inertial scale (~10 m) !!!!

Current sheet observations



6.4×10^4 km (Lin *et al*. 2007) from the UVCS data in Lyα

$4.0\times10^4 – 3.5\times10^5$ km (Ciaravella & Raymond 2008; Cairavella et al. 2013) from the UVCS data in [Fe XVIII]

10^5 km (Lin *et al*. 2009), 2.1×10^5 km (Schettino *et al*. 2009)

5.0×10^5 km (Lin *et al*. 2009), 3.0×10^5 km (Vrsnak *et al*. 2009) from LASCO data

A few times 10^3 km (Savage *et al*. 2010), 1.3×10^5 km (Landi *et al*. 2012) from Hinode/XRT data

3.7×10^4 km (Ling et al. 2014) from MK4 MLSO

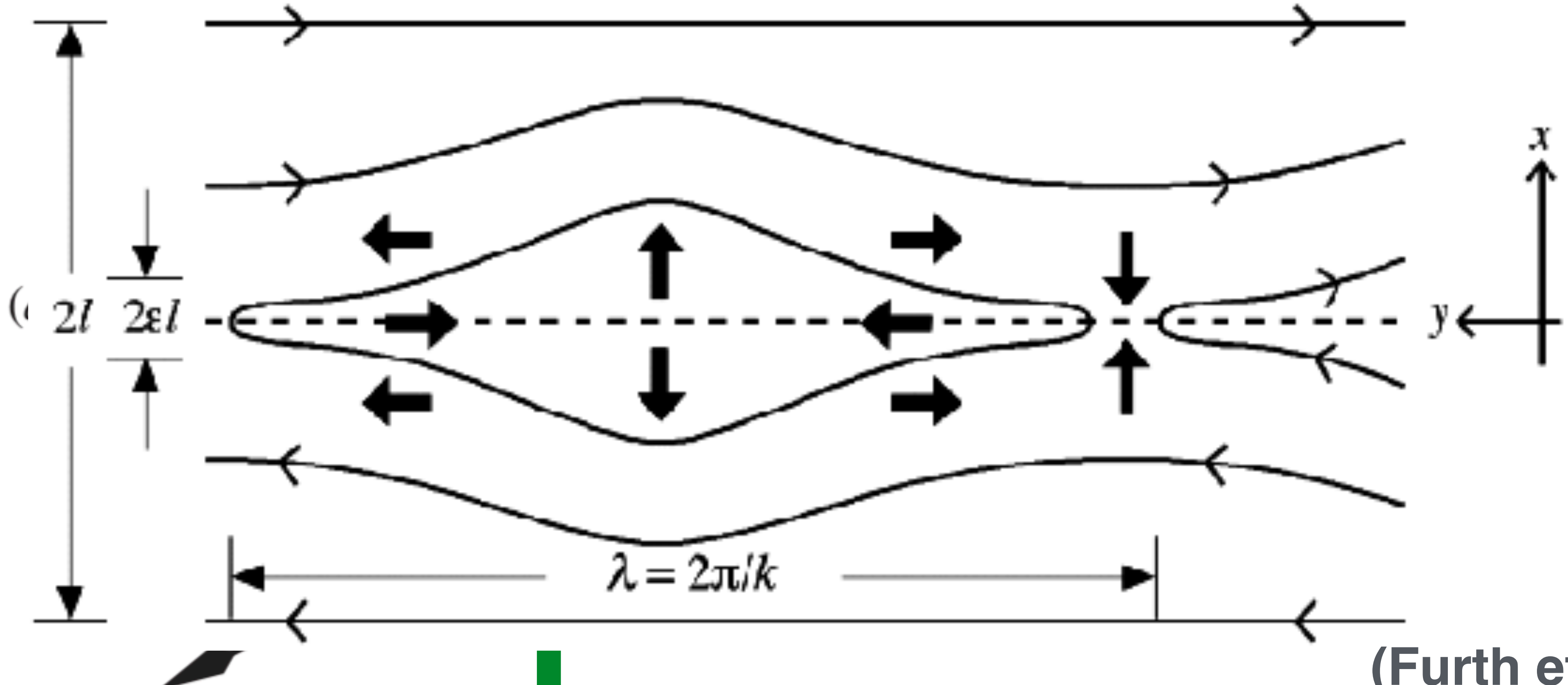
2.38×10^5 — 3.50×10^5 km (Kwon et al. 2016) from STEREO and LASCO

1.72×10^3 — 3.83×10^4 km (Seaton et al. 2017) from SDO/AIA

Thickness ~10^4 km to about 10^5 km >> tens of meters

(Lin et al. 2005; 2015)

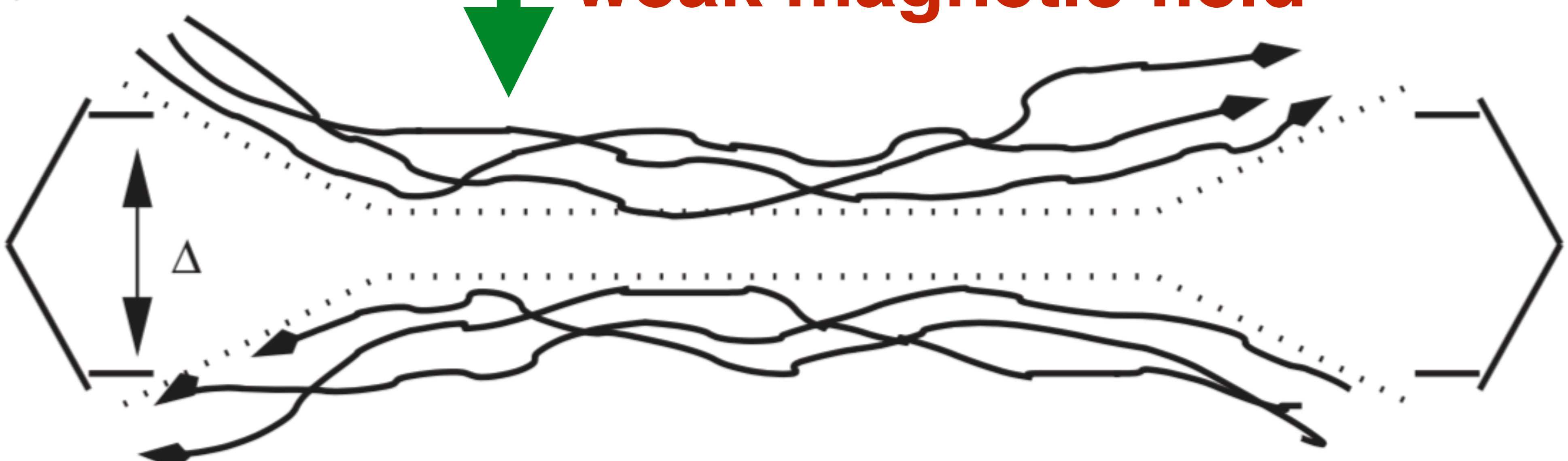
Turbulent magnetic reconnection



(Furth et al. 1963)

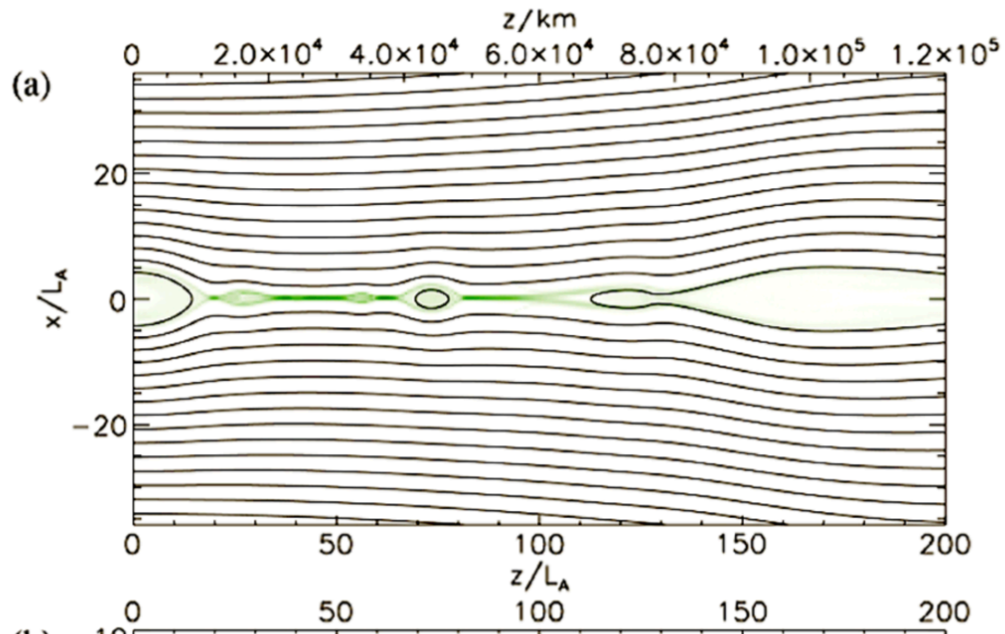
weak magnetic field

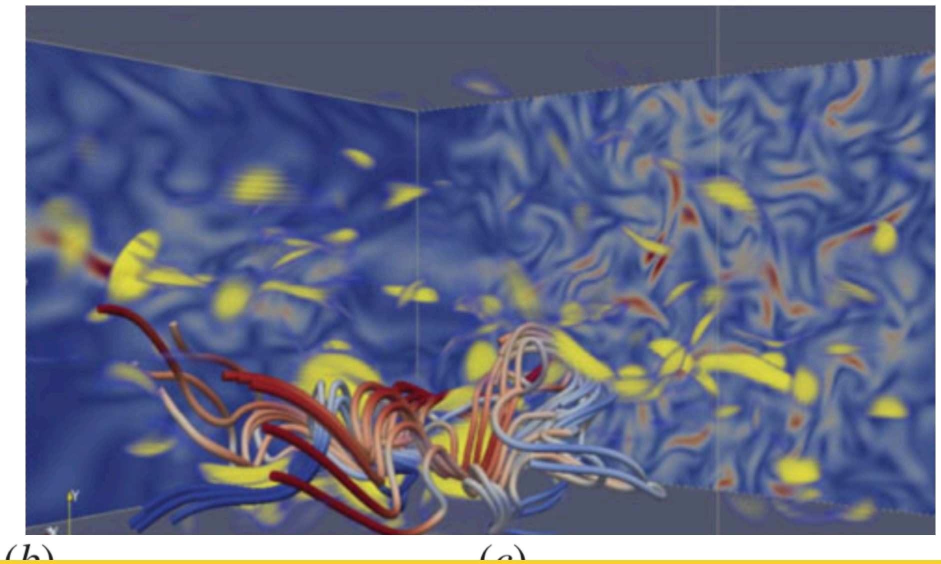
(b)



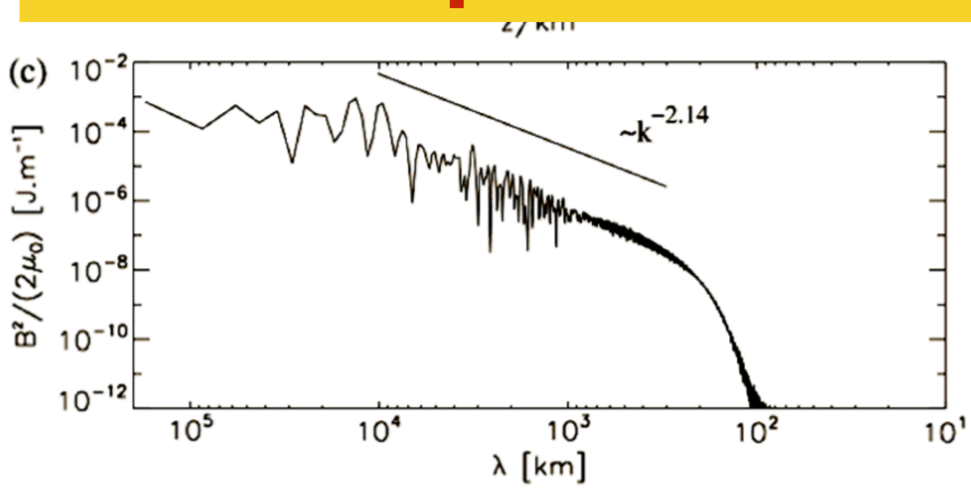
(Lazarian & Vishniac 1999; Shibata & Tanuma 2001)

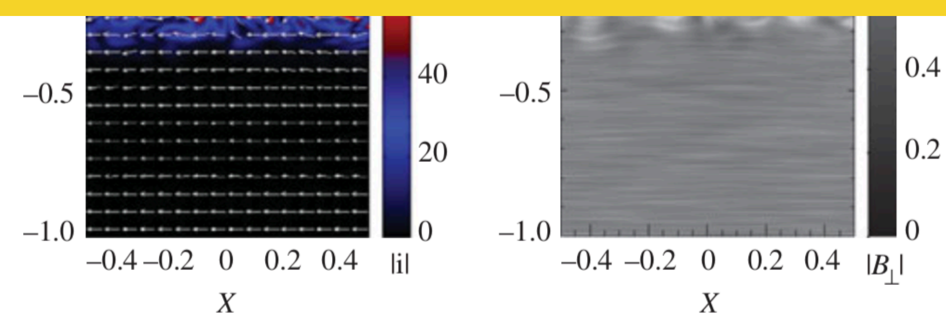
MHD and PIC simulations





Can we observe plasmoids and turbulence in the reconnection region during solar eruptions? How does it show itself?



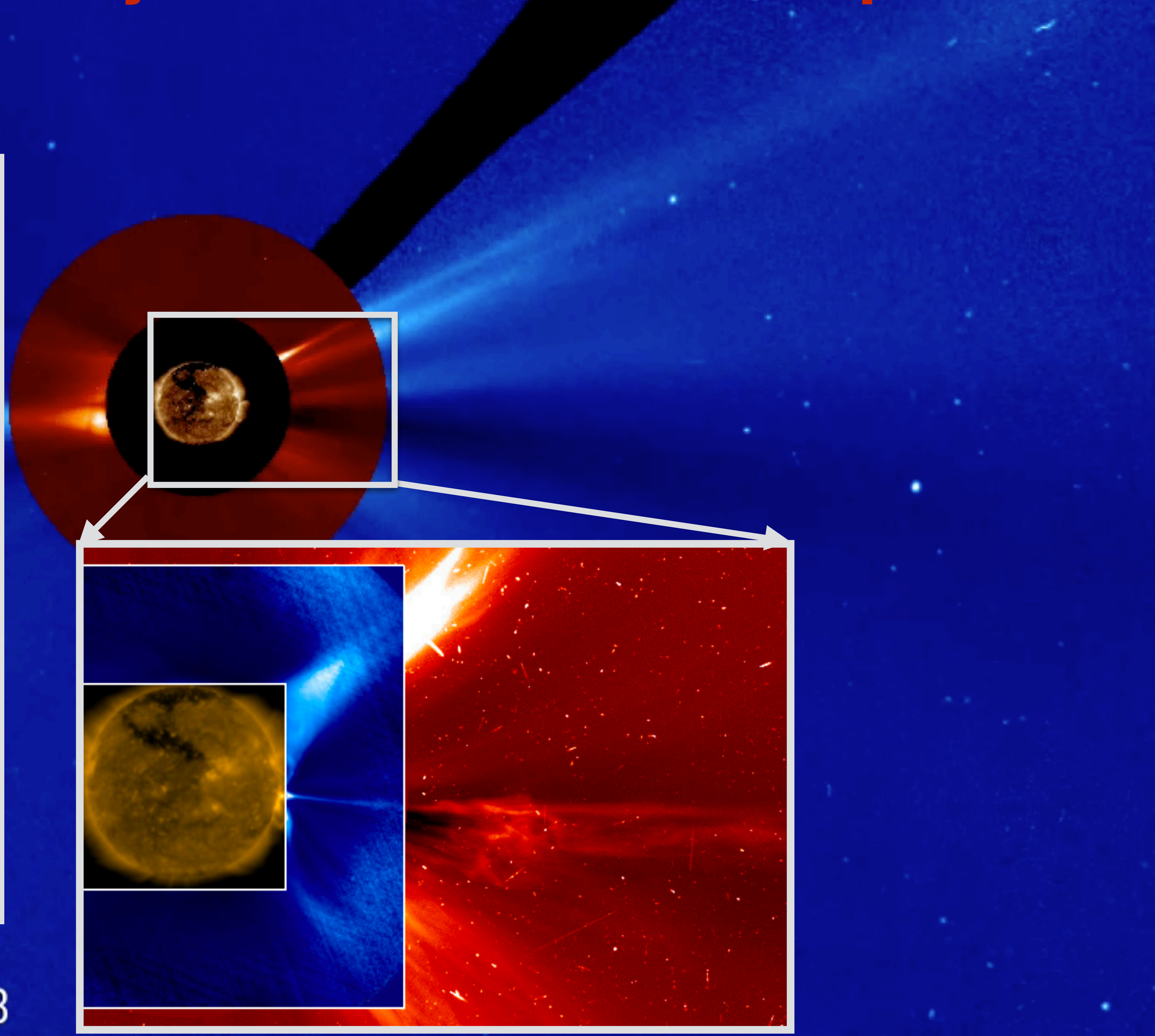


(Kowal et al. 2009, 2012; Daughton et al. 2011)

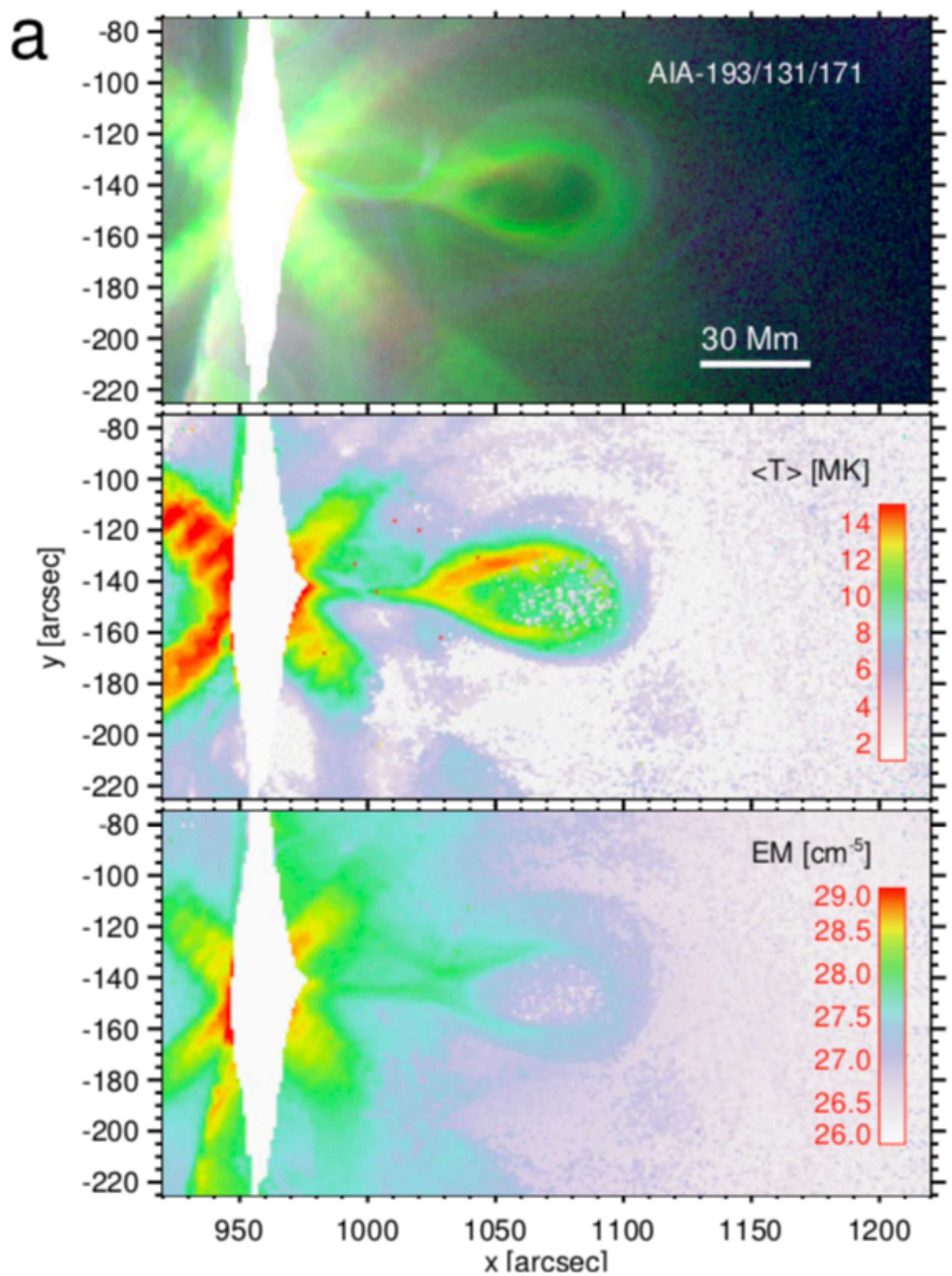
(Barta et al. 2011; Huang & Bhattacharjee 2012, 2017; Dong et al. 2018)

A tale told by 2017-09-10 CME eruption

- Very fast CME with a speed of 3000 km/s and the second largest flare in the past ten years,
- The linear structure connecting the CME bottom and flare top is clearly observed and that appears to be very dynamic.
- Similar to 2D picture of solar eruption by Lin & Forbes (2000).



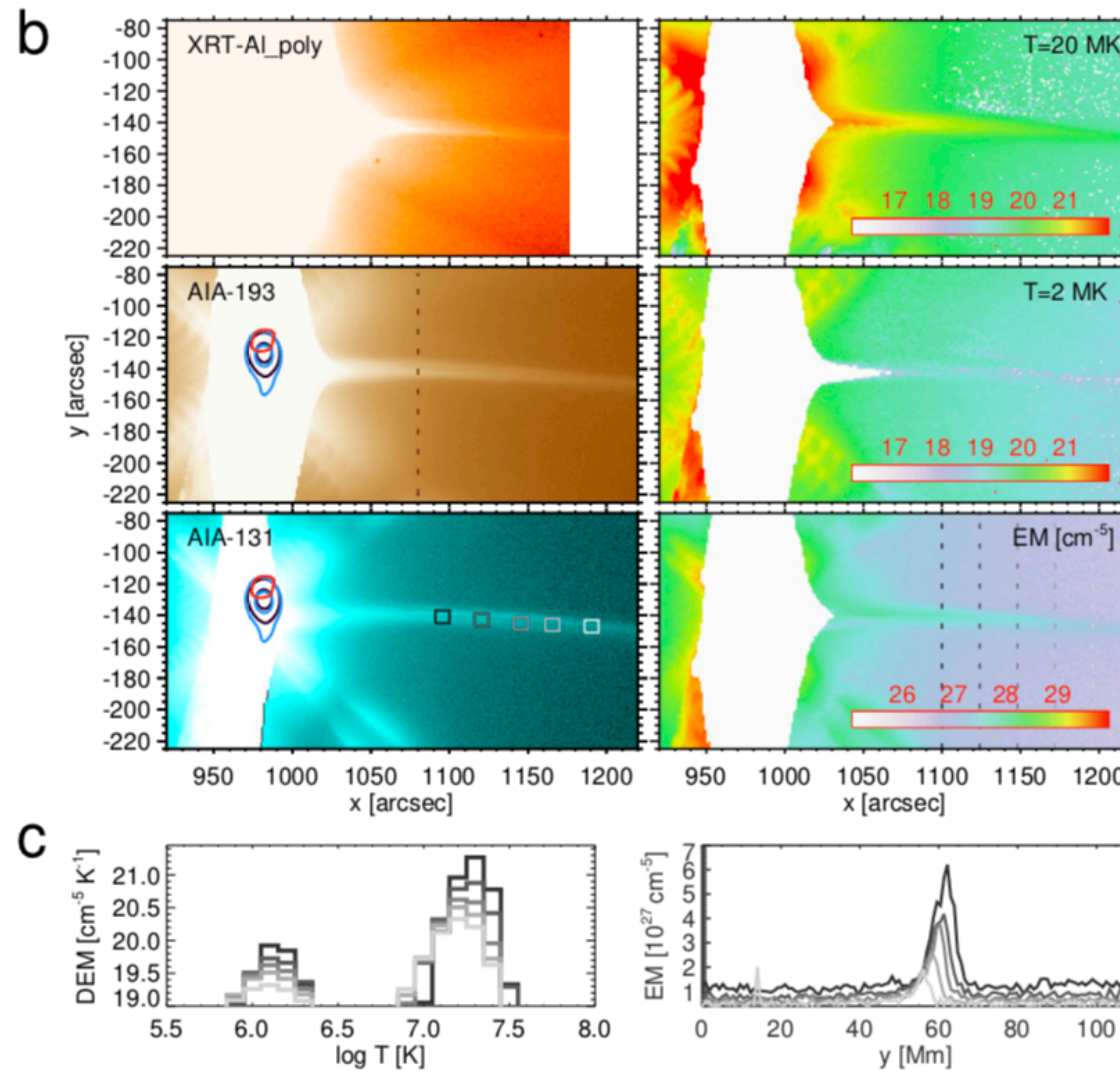
A tale told by 2017-09-10 CME eruption —hot blob eruption



- The loop-like structure ascends to a height of 90 Mm and appears as a well defined bubble consisting of a ring-shaped envelop and a low emission cavity, both of which are visible at most EUV and X-ray passbands.
- An elongated bright structure connecting the bottom of the bubble and the top of the flare loops.
- The cavity has a low EM of ~10^{26} cm^{-5} but high temperature of ~10 MK. By contrast, the bubble envelope (or the ring) and the current sheet have a much higher EM of ~$10^{27.5}$ cm^{-5} and an even higher temperature of ~13 MK, may due to newly reconnected hot flux.

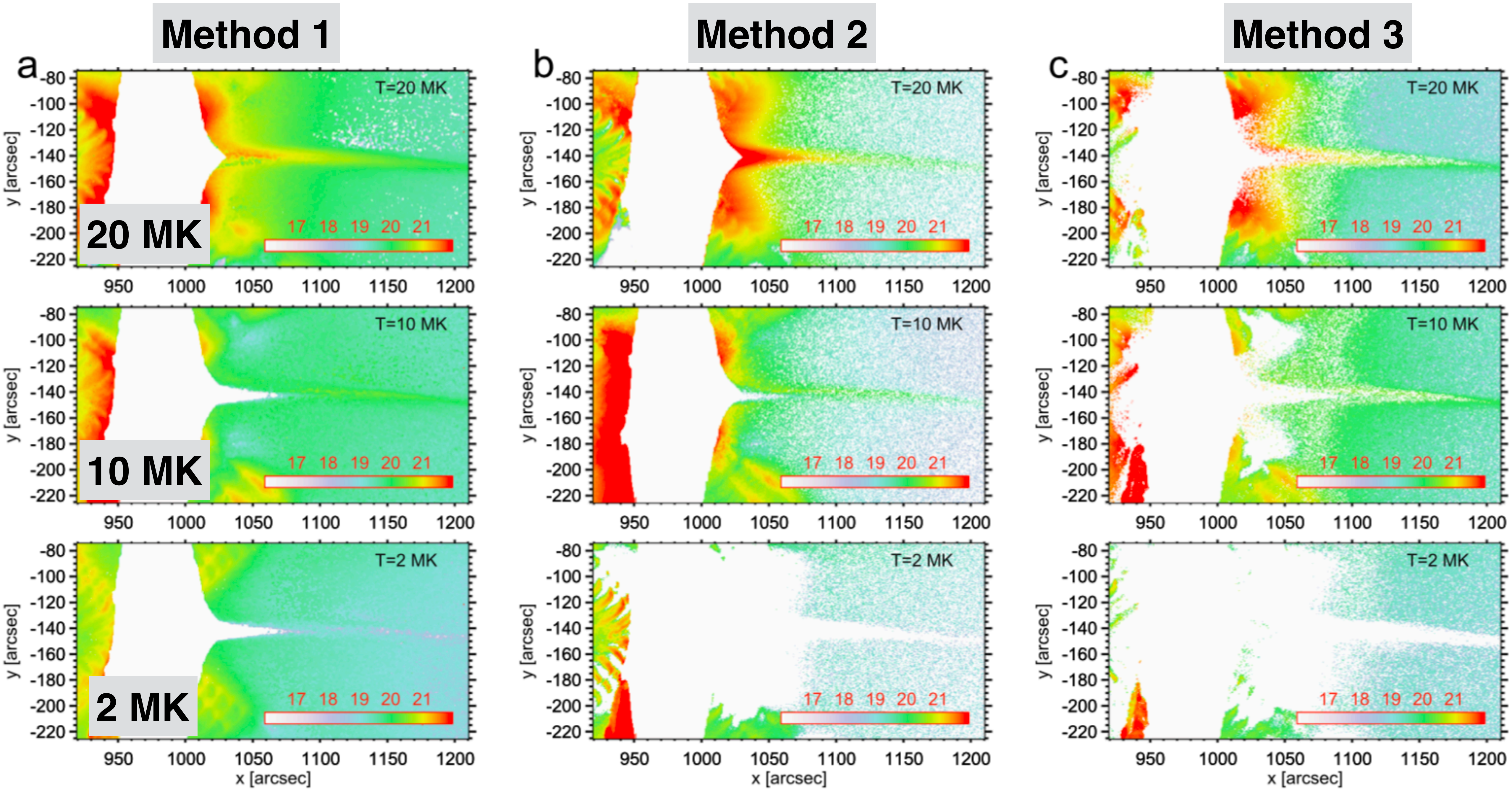
A tale told by 2017-09-10 CME eruption —super-hot current sheet

- At ~16:15 UT, the lower end of the current sheet ascends to a height of at least ~100 Mm, containing high super-hot plasma (Figure 1b), which is also confirmed by the EIS Fe XXIV 192.03 and 255.11A lines.
- The plasma is primarily distributed near the temperature of 20 MK with the total EM of 1–5×10^{27} cm^{-5} (Figure 1c). The density is ~0.6–1.3×10^{9} cm^{-3} assuming a depth of 30 Mm (the size of the bubble) at the height of 100–200 Mm.
- The average width of the current sheet is estimated to be ~10 Mm at the height of ~150 Mm (Figure 1c).



(Cheng et al. 2018 ApJ)

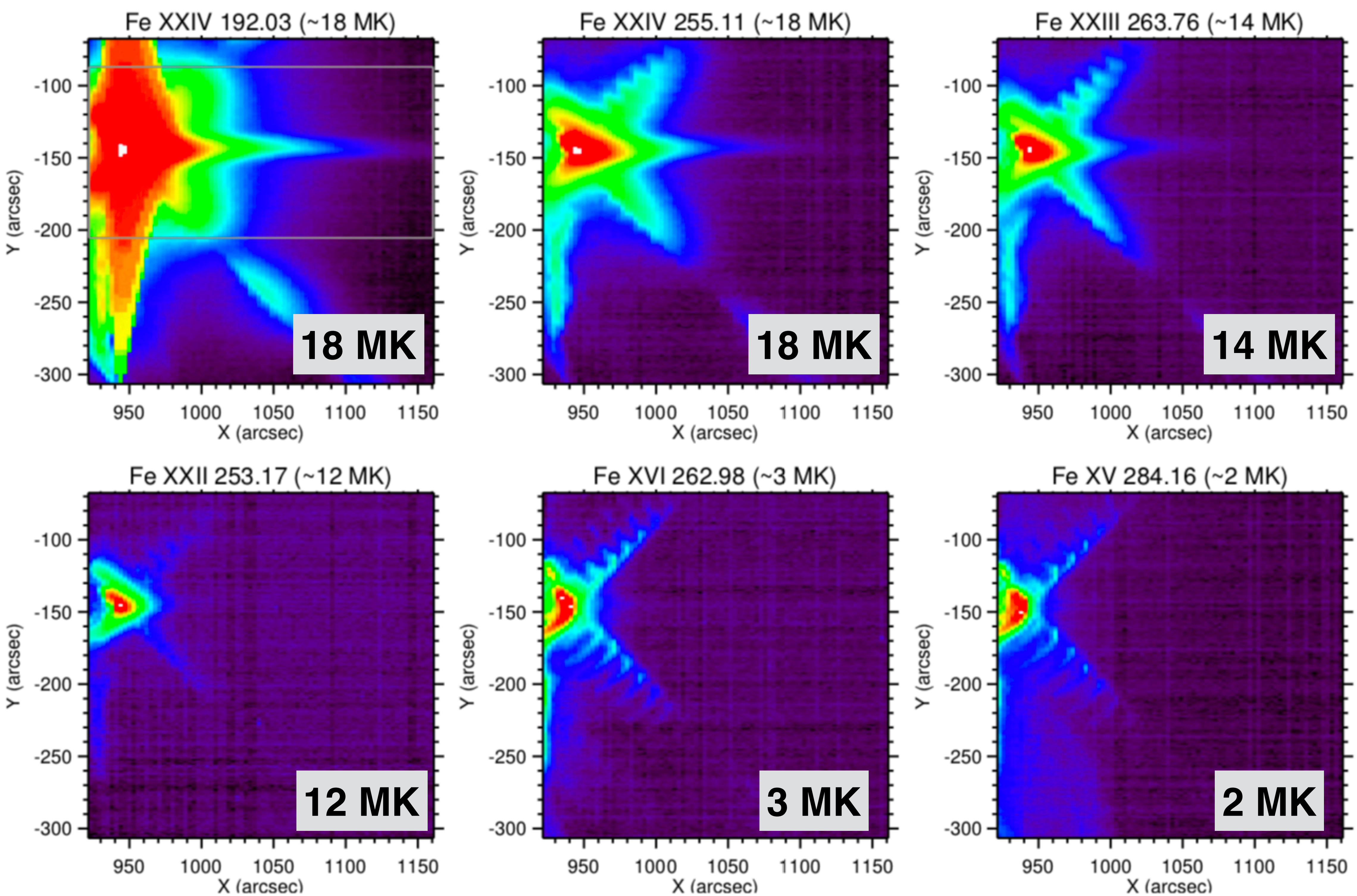
Super-hot CS justified by different methods



Current sheet is super hot with a temperature of 20 MK!

EIS observations

Super-hot current sheet confirmed by EIS spectral lines

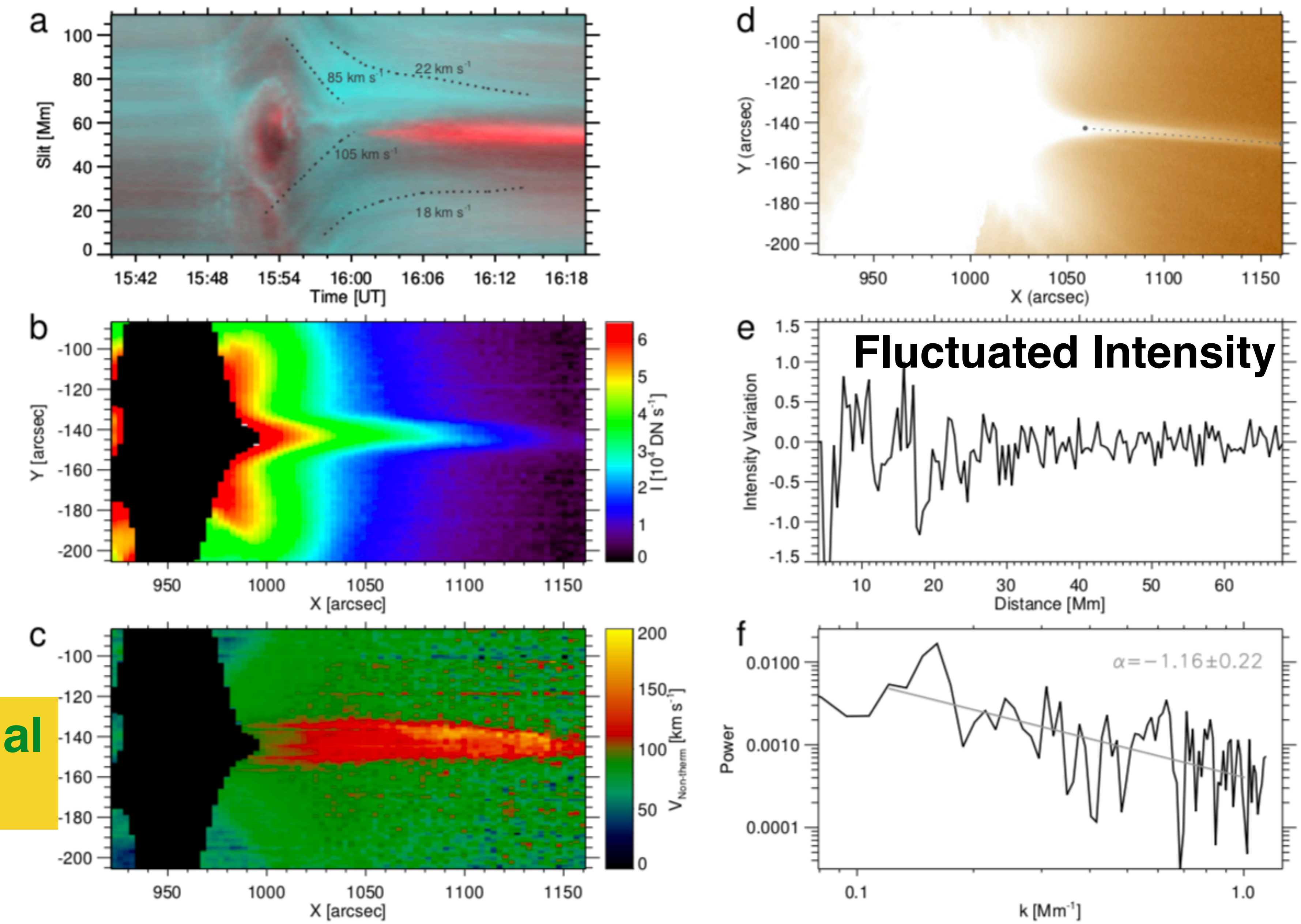


Turbulence and fragmented current sheet

Inflows heating

Fe XXIV

Non-thermal velocity



193 image

detrended intensity

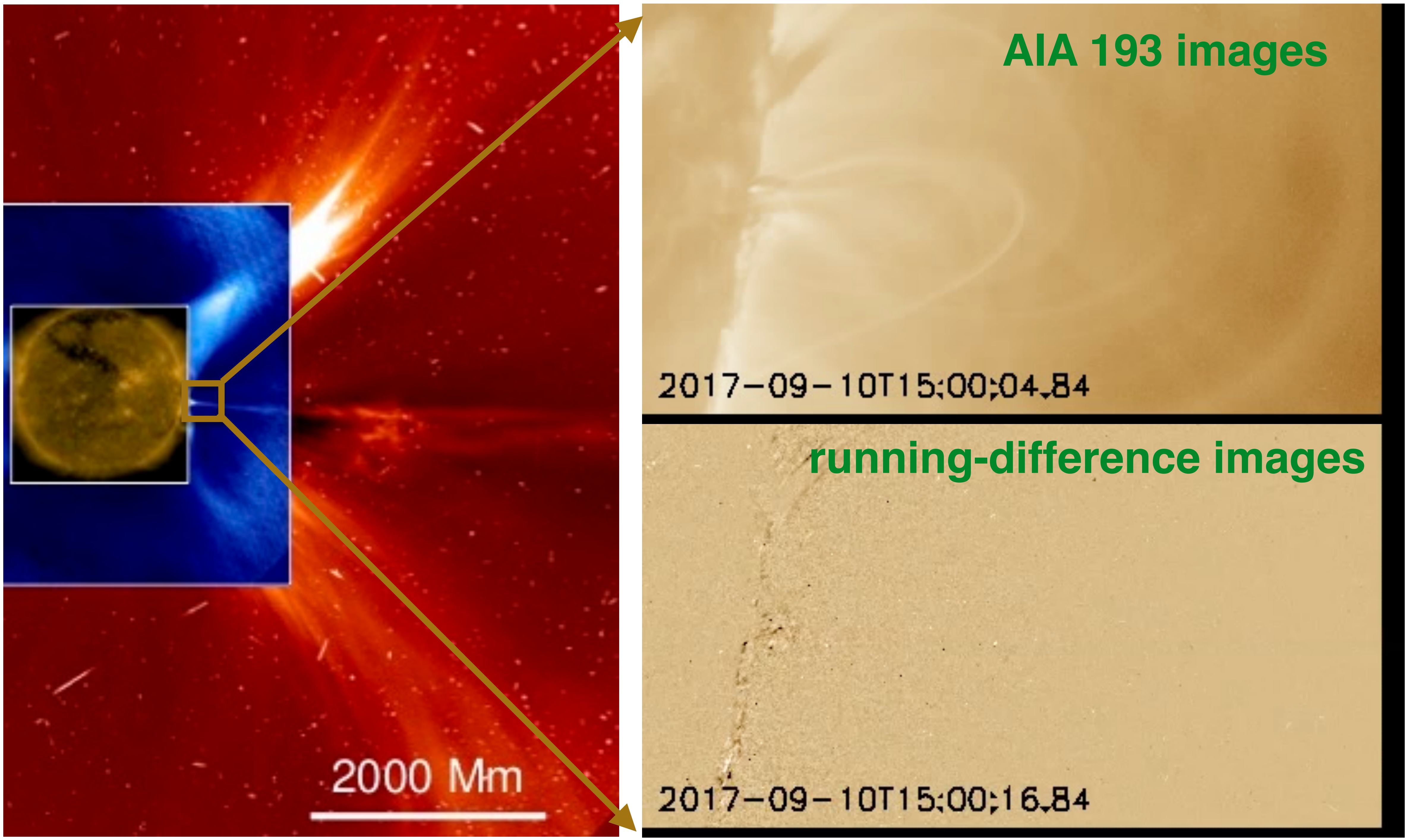
power spectrum

significant non-thermal —> turbulence?

fragmented current sheet —> plasmoids

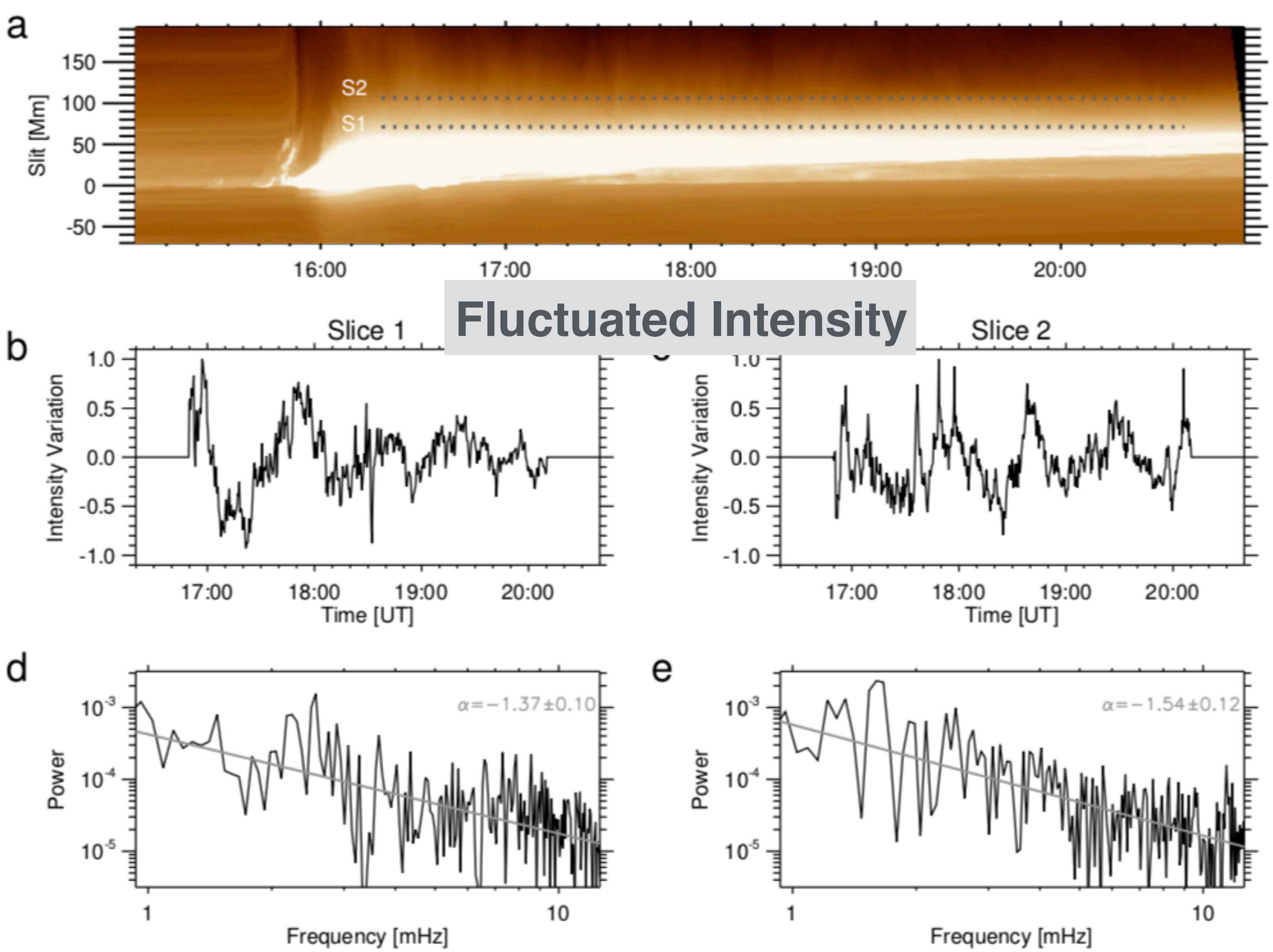
(Li et al. 2018 ApJL; Cheng et al. 2018 ApJ)

Intermittent sunward outflows from the CS



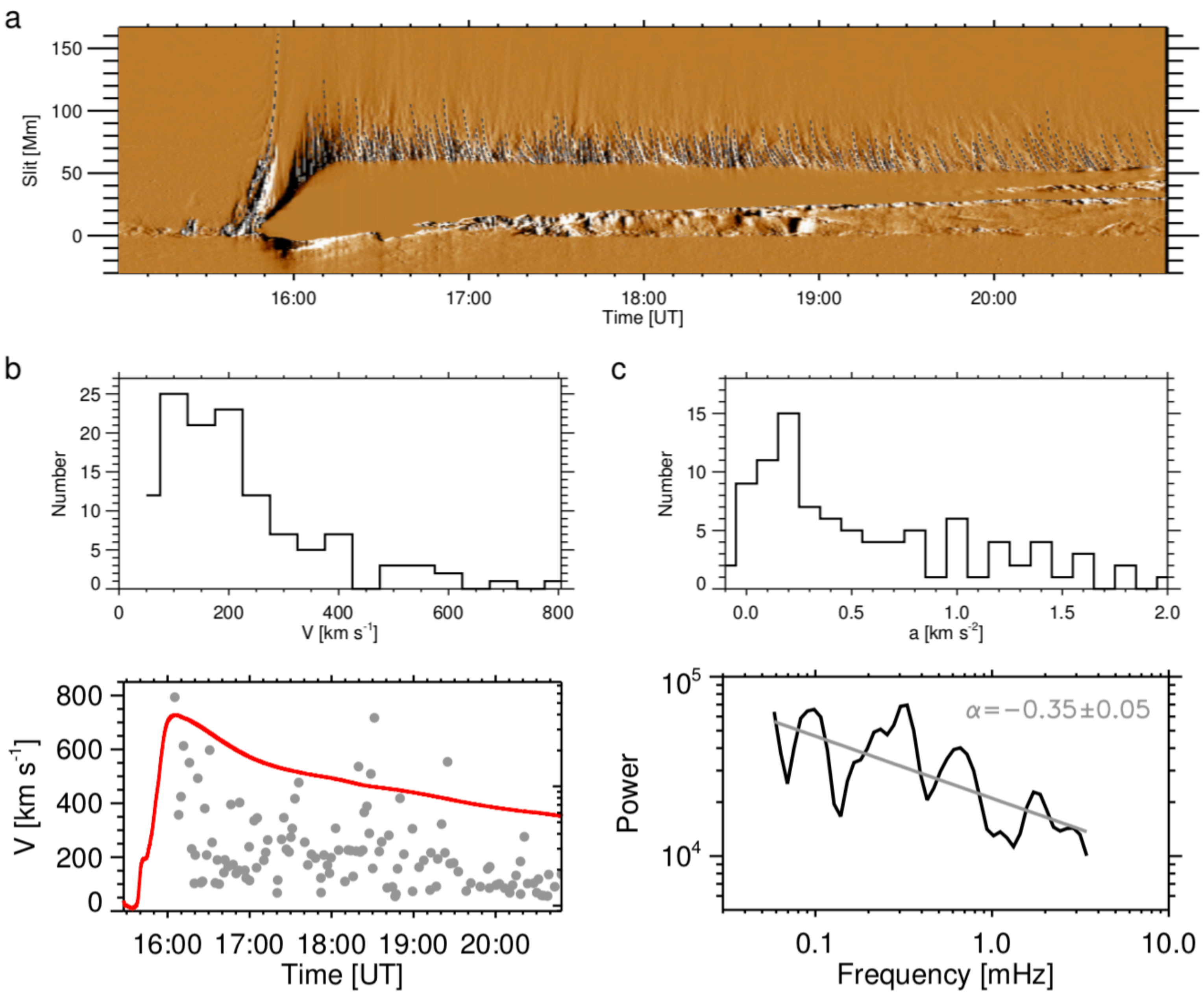
(Cheng et al. 2018 ApJ)

Intensity fluctuation of intermittent outflows



- ☑ The 193 intensities in the outflow regions also present fluctuations,
- ☑ The spectral index varies from -1.3 to -1.8, indicating that the outflow jets may be widely distributed in energies.

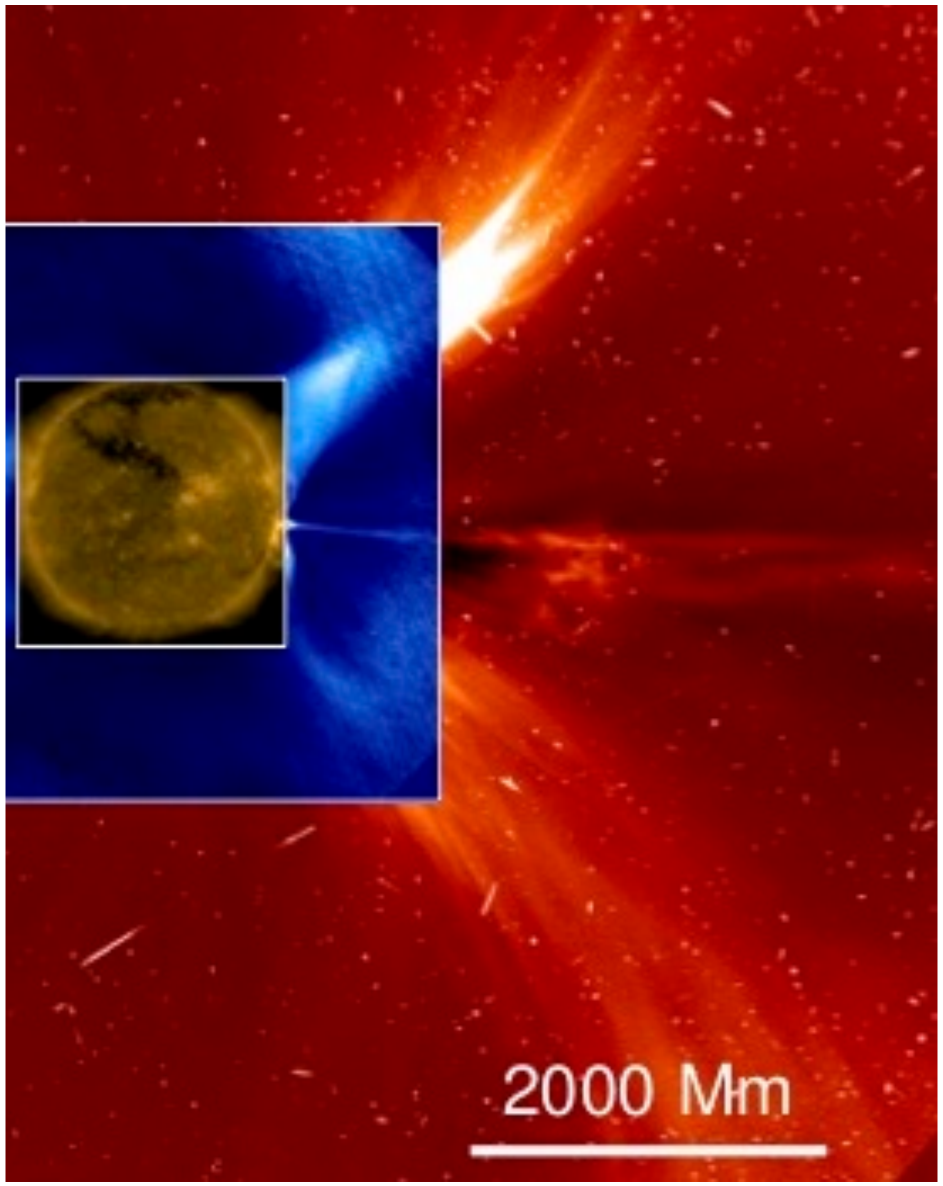
Velocity diversity of the outflow jets

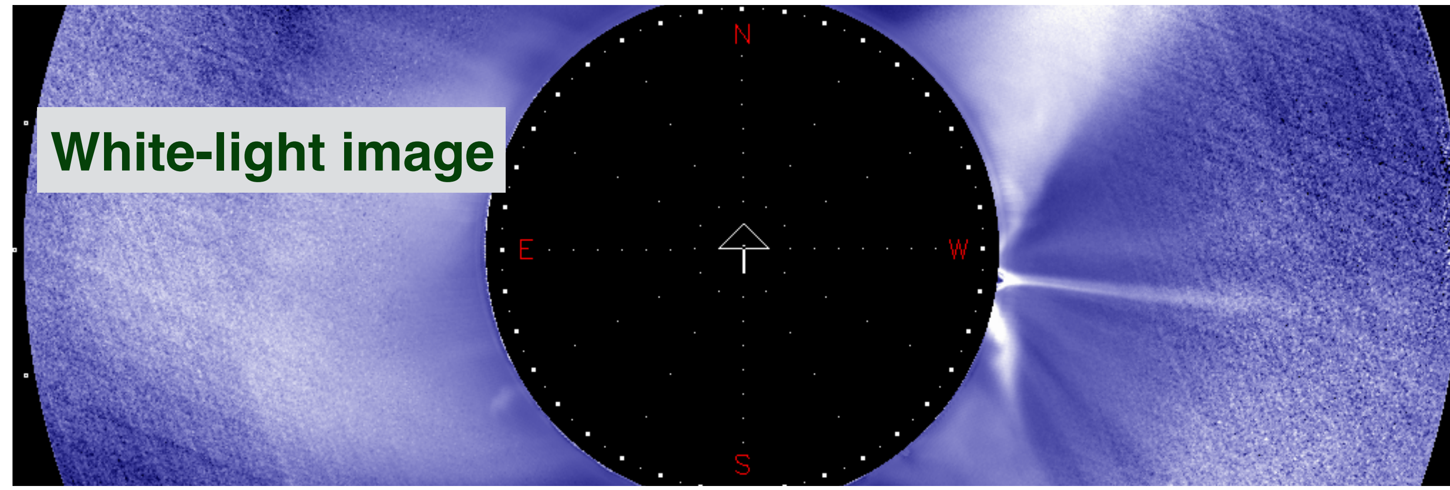


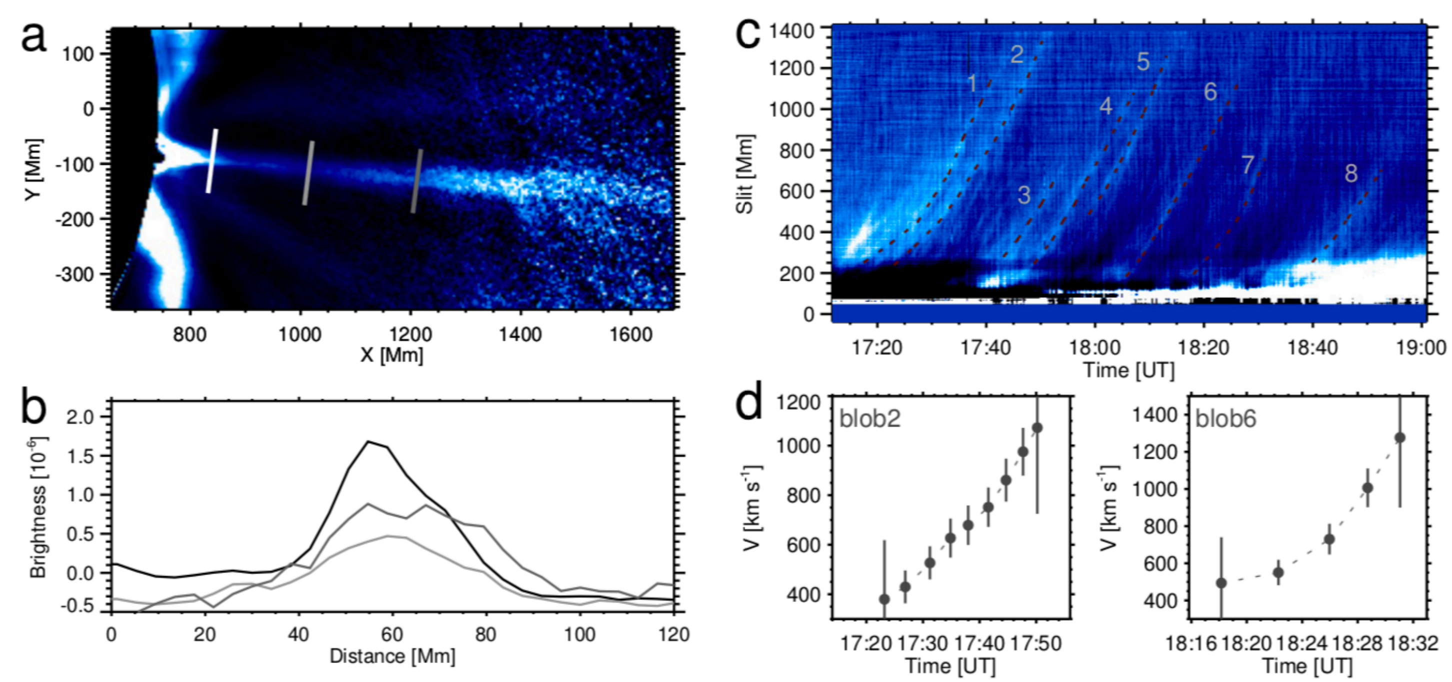
- The initial velocities and accelerations of the jets have **a wide distribution**,
- They also present a **power law spectrum**, implying that the reconnection is modulated by turbulence,
- Taking the inflow velocities of 20 km s^{-1} near the flare peak time, **the reconnection rate ranges from 0.003 to 0.2.**

(Cheng et al. 2018 ApJ)

Intermittent anti-sunward outflows







- The anti-sunward blobs are intermittently formed in the current sheet, the velocity increases with time.
- The length-to-width ratio is high up to 200 >> threshold of tearing mode instability (2pi), allowing the appearance of magnetic islands.

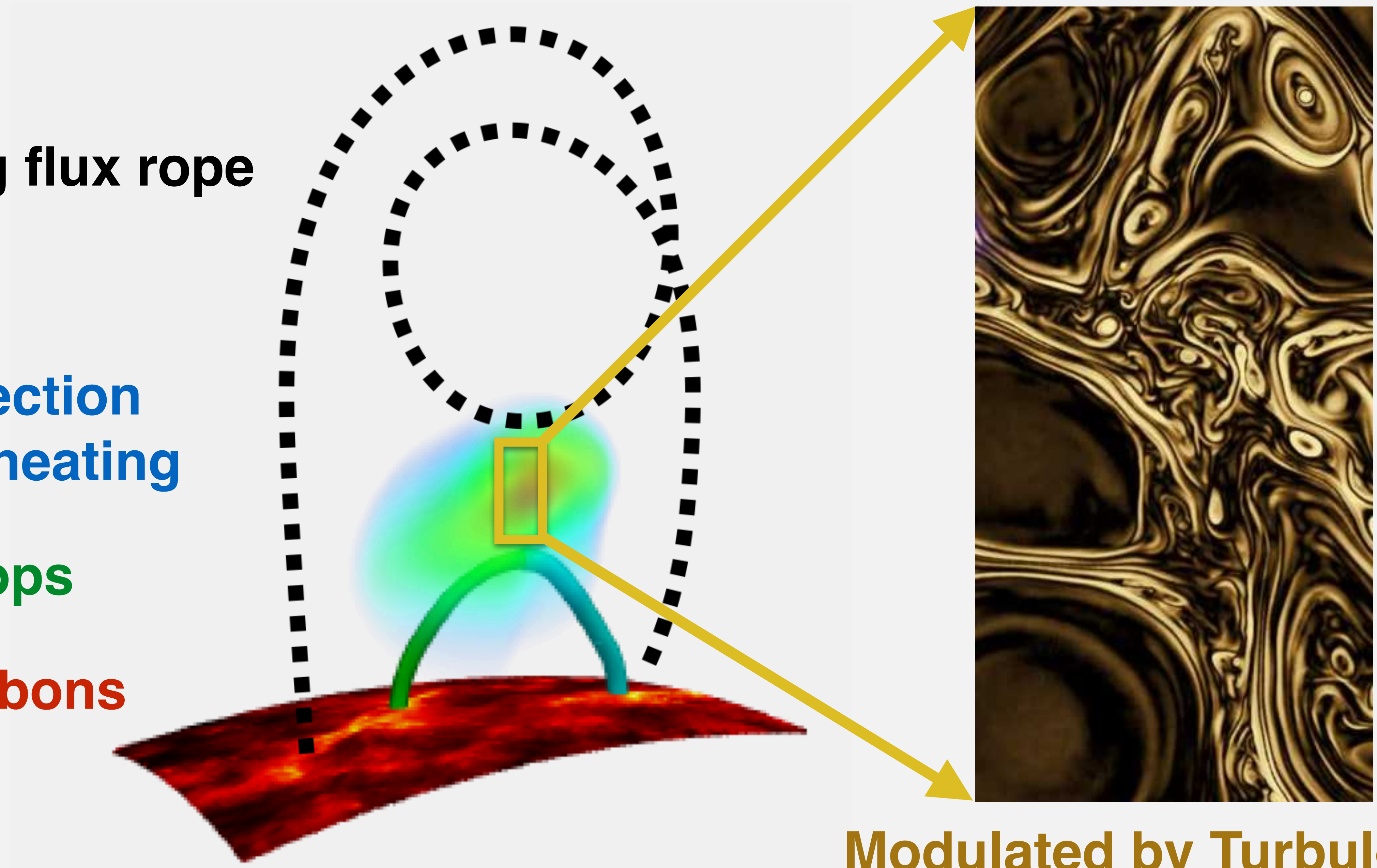
Solar eruption powered by turbulent reconnection?

Erupting flux rope

Reconnection
Plasma heating

Flare loops

Flare ribbons

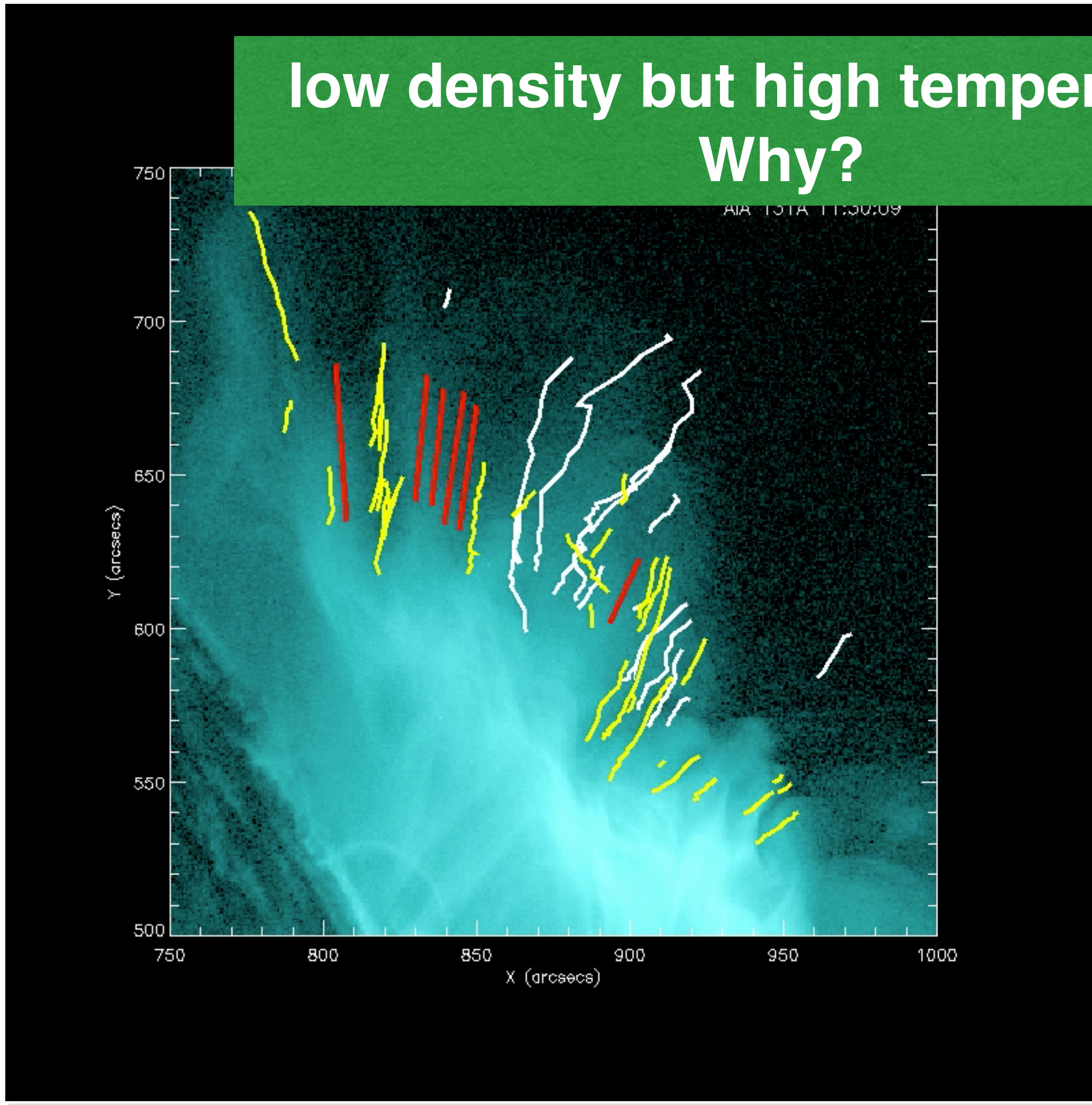


Modulated by Turbulence

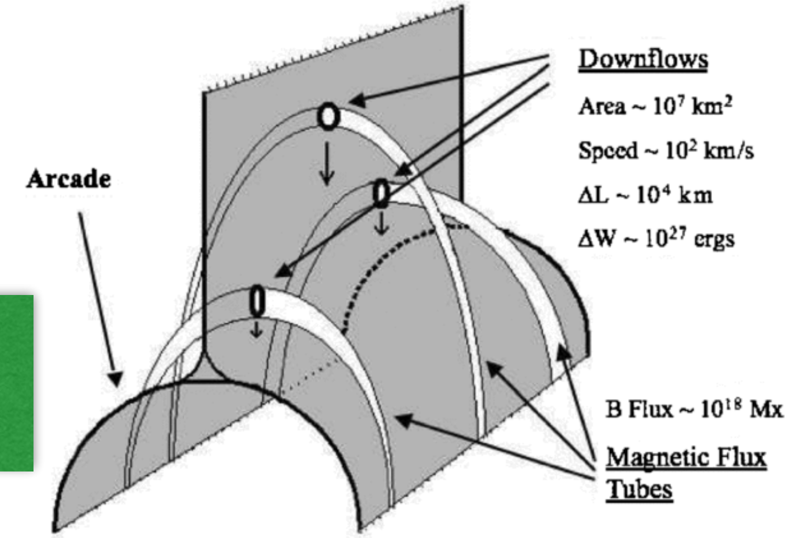
(Sun, Cheng et al. 2015; Cheng et al. 2018)

Still puzzled!

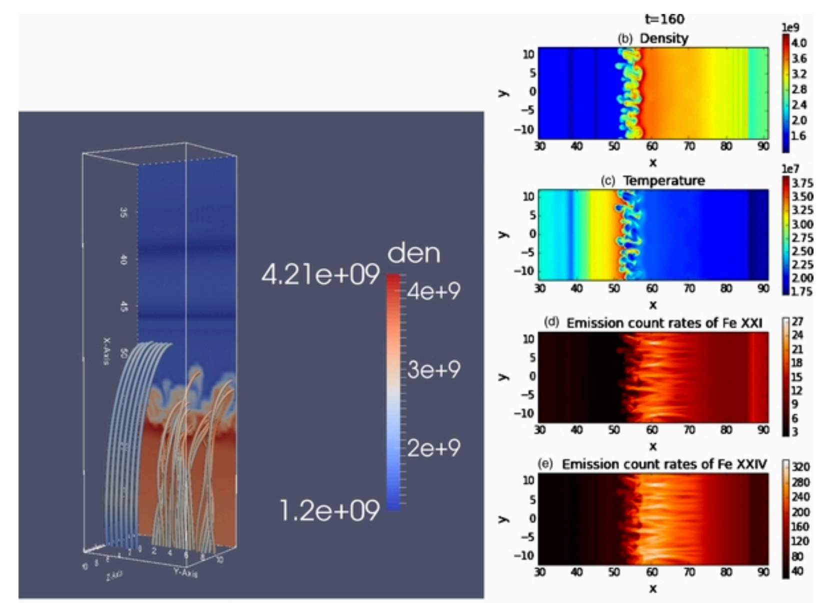
low density but high temperature!
Why?



Reeves et al. 2017



Downward moving flux tubes
McKenzie & Savage 2009



Rayleigh-Taylor instabilities
Guo et al. 2014

A high resolution MHD simulation that considers real configuration and parameters is required to reveal more details comparable with real observations!

Conclusions:

1. Magnetic flux ropes exist in the corona, even prior to the eruptions, appearing as a hot channel with temperature at 10 MK.

2. Early formation and acceleration of CMEs and the variation of flare emission are determined by the dynamics of flux ropes.

3. Topology of reconnecting magnetic loops is 3D during CME/flares, requiring an extension of 2D CME\flare model to 3D,

4. Magnetic reconnection occurs in a fragmented and turbulent way within the long stretching current sheet in the wake of CMEs, more details are expected from PSP and Solar Orbiters!


Thanks for your attention!!